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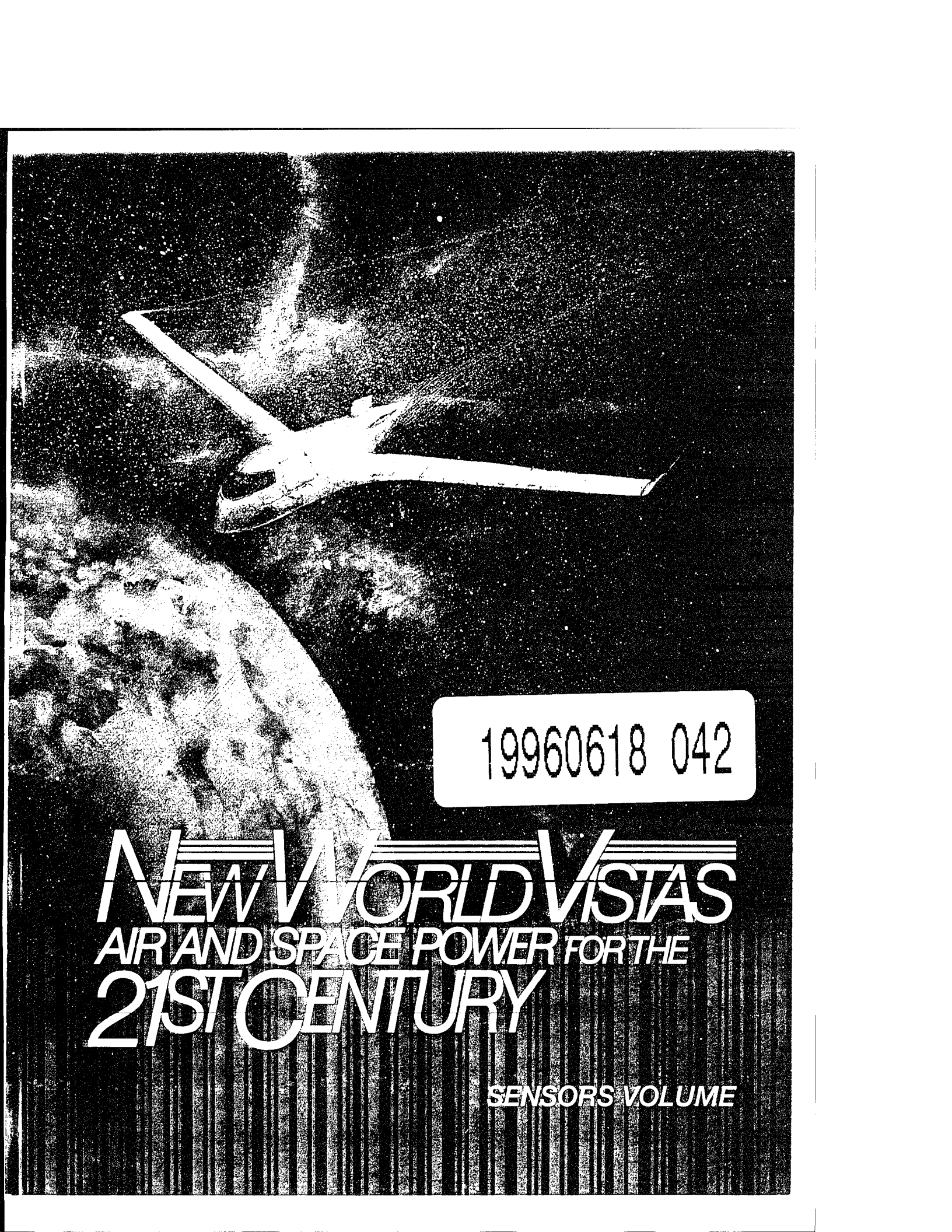
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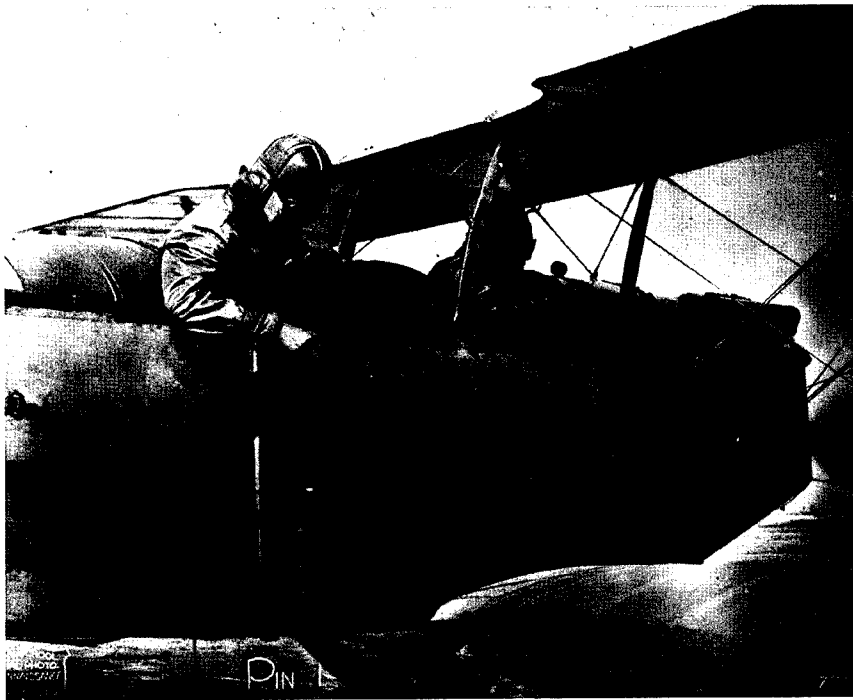## AIR AND SPACE POWER FOR THE 21ST CENTURY

SENSORS VOLUME

NEW WORLD VISTAS
AIR AND SPACE POWER FOR THE
21ST CENTURY

SENSORS VOLUME

This report is a forecast of a potential future for the Air Force. This forecast does not necessarily imply future officially sanctioned programs, planning or policy.

Executive Summary

Sensors Panel

"To Know More and To Know It Sooner"

Introduction

Sensors are essential elements of virtually every Air Force (AF) weapon and support system. The hardware and software associated with sensing functions are generally major, and sometimes predominant, contributors to the performance, reliability, supportability, and cost of such systems. Many of the technologies associated with sensors are in a state of rapid evolution and will remain so for the foreseeable future. Moreover, many sensing functions and devices that are important to the Air Force have counterparts in commercial, industrial and medical applications. This combination of ubiquity, operational impact, technology leverage, and dual use potential makes the subject of sensors especially important to the themes of *New World Vistas*.

Sensors have played an important military role in the past and will play an increasingly important role in the future as air power is called upon to respond to a wide range of conflicts and to apply force with exquisite precision, no collateral damage, and nearly instantaneous response. Sensors provide data and information that lead to increased knowledge about our own and the enemy's forces, circumstances in the battlespace, and, ideally, the enemy's plans and intentions. Knowing more and knowing it sooner than the enemy provides an advantage and motivates the goal of acquiring "near perfect" knowledge of the battlefield as well as overall global situation awareness at any time and under any weather condition. The growing emphasis on smarter and smarter weapons, the difficulty of detecting and identifying concealed targets, the growing concern about proliferation of inexpensive cruise missiles and weapons of mass destruction, the need for precise target information and the detailed information needed for counter-terrorism activities are all additional examples that motivate the desire for larger numbers of better and more affordable sensor systems.

Sensors represent a very broad and pervasive class of measurement systems. Sensors can exploit the full electromagnetic spectrum by intercepting reflected or naturally occurring electromagnetic radiation; detect various forms of mechanical energy, for example, seismic and acoustic; and physically sample and analyze a diverse set of chemical and biological components. Moreover the sensors can be active or passive, where an active sensor is one that stimulates its external environment and measures a reflection or other response, and a passive sensor is one that does not. Sensors can be operated from a variety of platforms in space, in the air, on the surface or below the surface of the earth. The sensors can be operated from stationary platforms or moving vehicles that can be inhabited or not. Indeed, many of the sensors of the future may be transported by small, mechanical, crawling or flying devices. Section 2 of this Volume is a discussion of the sensing process in general which establishes a framework for systematic treatment of this exceptionally diverse topic. Tables 1 and 2, on following pages, present a sampling of the taxonomies developed in Section 2 to give a sense of the range of sensor types and uses with which we must deal.

Table 1. Examples of Active and Passive Sensor Types Employing Various Phenomenologies

Physical Phenomenon	Active Sensor Types	Passive Sensor Types
Electromagnetic • DC/Low Frequency		Conductivity, Squid, Magnetometer
• RF Wavelengths	Radar, IFF	CNI, SIGINT, Radiometer, ESM, RWR
• EO/IR/UV Wavelengths	LADAR, LIDAR, X-Ray	FLIR, IRST, NVG, TV
Mechanical • Acoustic	Ultrasonic NDI, Active Sonar, Radio-Acoustic Sounder	Microphone, Hydrophone/Passive Sonar
• Seismic	Active Tomographic	Geophone/Seismometer
• Tilt		Tiltmeter
• Inertial		Micro-IMU, Accelerometer, Gyro
Chemical/Biological	Differential Absorption LIDAR (DIAL)	Spectrometer, chemical reaction Flow-PCR Mass Spectrometry SAW-based selective adsorption Enzyme-based electrochemical UV-fluorescence spectroscopy

Table 2. Examples of Sensors Used for Various Operational Tasks

Sensor Applications	Typical Sensor Types
Wide Area Surveillance	Radar (AWACS, Joint STARS, OTH, etc.), Passive EO, SIGINT
Threat Warning	Passive EO (missile launch detection/approach warning), RWR, CNI/ESM, SIGINT, Radar
Reconnaissance/Battle Damage Assessment	Imaging EO, Imaging Radar, ESM, Fire Control Sensors
Air-to-Air Detection, Tracking, & Fire Control	Radar, IRST, ESM (e.g., ARM seeker)
Air-to-Ground Targeting & Fire Control	Radar (SAR), FLIR, LADAR, ESM
Missile Guidance	Inertial, Stellar, GPS, Radar, LADAR, Passive EO, ESM, Beam Rider, Proximity Fuze
Navigation	Inertial, GPS, Imaging Radar, Stellar, CNI
NBC Detection	Specialized Detectors, DIAL, Hyperspectroscopy, LIDAR
Ground Traffic	Acoustic, Seismic, including UGS
Weather	Radiosondes, Doppler Radar, Imaging EO
Science and Technology (S&T)	Imaging EO and Radar, ESM/SIGINT
General Intelligence and Indications and Warning (I&W)	ESM/SIGINT, Imaging EO and Radar, Wire Taps, Acoustic/Seismic, UGS
Medical/Crew Health Monitoring	Multiple Biomedical Instruments
System Health Monitoring	TSMD, Built-In Fault Detection/Isolation, NDI

Observations

We are at the threshold of the fourth revolution in military "sensing" that started with the human observer and is now leading to real time remote sensing worldwide. In the first phase of reconnaissance and surveillance, the human observer provided direct input–eyes on target–to the field commander for his direct action. For this early history of warfighting, the range of direct action (such as arrows and cannon fire) was well matched to the sensory range of the human observer. As extended range artillery, rockets and the airplane increased the range of action, reconnaissance changed from balloons observing over the trenches to airplanes with film cameras. However, with the extended range of sensors, came a penalty to the field commander in terms of timeliness. To improve responsiveness, the third revolution of real time sensing systems was developed and fielded. We now find our reconnaissance capabilities based on a few high performance systems that must be shared across all field commanders. Changes in the velocity of maneuver, range and precision of theater weapons and the potential use of WMD require a revision in our sensing system strategies.

As we enter the fourth phase of military sensing, we must detect a wide spectrum of target information ranging from traditional solid targets, for example tanks, to chemical and biological effluents. The implementation of this phase is beginning with low cost UAVs distributed among supporting commanders at all echelons. This concept, taken to conclusion, leads to a wide variety of low cost micro-sensors providing warning, targeting, and battle damage assessment. The use of distributed micro-sensors is not new to the military; but historically, these sensors have been expensive and cumbersome and applicable to only the highest priority national problems. Recent developments noted above present new opportunities for the use of these sensors. They may be used for distributed surveillance and targeting as well as for enhanced sensing that is difficult with current sensors. They may also serve to increase the survivability of larger conventional surveillance and reconnaissance systems while reducing the operational costs. These and other concepts related to the fourth revolution in sensing are reflected throughout this Volume of *New World Vistas*.

Stressing Operational Tasks

We have approached the future of sensor capabilities and systems from the logical extremes of operational pull and technology push. First, we have derived seven representative operational tasks in which sensor capabilities are prominent and which stress the current state of those capabilities. Section 4 of the Volume spells out in some detail the nature of each of these representative tasks and the associated sensor capabilities needed to support the warfighter in each scenario.

The representative operational tasks are listed in Table 3, along with samples of the sensor concepts associated with each. These tasks span the operational spectrum in such a way that an inventory of fielded sensor systems that adequately satisfies these needs would be highly competent in virtually any operational scenario.

We have also identified some of the key enabling technologies associated with the operational tasks. These are summarized in Table 4. In parallel, we have extensively surveyed the overall sensor technology arena, including receiving extensive briefings and papers from leading R&D organizations. From the many dozens of interesting technology ideas thus identified,

Table 3. Representative Operational Tasks and Associated Sensor Capabilities

Stressing Operational Task	Typical Related Sensor Capability
Acquire, maintain, and disseminate a full, near-real-time situational awareness picture of the battlefield.	All-condition, high resolution imaging to detect, locate, and classify targets and activity patterns and build time histories.
Maintain continuous world-wide surveillance of nuclear, biological, and chemical (NBC) weapon manufacture, storage, and transfer.	Multispectral active sensors for detection and identification of trace chemical effluents from NBC facilities.
Locate, observe, and target assets and activities in hardened/underground facilities.	Seismic sensors capable of deriving 3-D conformations of underground structures.
Acquire, locate, track and identify air and ground targets to deliver munitions with high accuracy.	Combined imaging and moving target sensors to detect and locate moving targets in heavy clutter.
Detect, track, intercept, and destroy theater ballistic missiles and cruise missiles.	Internetted missile launch detection and tracking sensors.
Acquire, maintain, and disseminate information to plan and execute military operations other than war (MOOTW).	Special sensors for counter-terrorist and hostage rescue, for example, detection of personnel in buildings.
Acquire information for force sustainment.	Portable, nondestructive inspection instruments for flightline detection of corrosion, cracking, and delamination.

Table 4. Enabling Technologies

Operational Task	Enabling Technologies
Battlefield Situational Awareness	RF Conversion Moderate Power Tunable Lasers High Efficiency Solar Cells Mass Storage Devices Intelligent Agents High Rate, Highly Linear Analog-to-Digital Converters Fusion/Correlation Techniques Automatic Target Recognition
Surveillance of Weapons of Mass Destruction	Multispectral Laser Radar for Effluent Detection Low Cost Focal Plane Arrays Micro-Machinable Electromechanical Systems Materials Tagging Adaptive Tasking Information Fusion/Correlation Femtosecond Laser Radars Unattended Ground Sensors (Acoustic, RF, IR, Seismic)
Surveillance of Underground Facilities	RF/Seismic Sensors With Tomographic Processing Multispectral Laser Radar for Effluent Detection Unattended Ground Sensors (Acoustic, RF, IR, Seismic) HF/VHF Synthetic Aperture Radar Weapon Borne Battle Damage Assessment Sensor
Accurately Deliver Munitions	Multifunction EO/IR Modular, Multifunction RF Components 3-D Laser Radar Miniature, High Accuracy Inertial Measurement Unit Imaging IR Sensor Multispectral Laser Radar Automatic Target Recognition Weapon Borne Battle Damage Assessment Sensor
Find Theater Ballistic Missiles and Cruise Missiles	Space Based Radar High Energy Lasers Optical Fire Control System Unattended Ground Sensors (Acoustic, RF, IR, Seismic) HF/VHF Radar
Special Operations and Military Operations Other Than War	Miniature Focal Plane Array Chem Lab On a Chip Multispectral Apertures RF Sensors Multispectral Laser Radar for Effluent Detection Unattended Ground Sensors (Acoustic, RF, IR, Seismic)
Force Sustainment	BIT/FIT Sensors Corrosion Sensors Crack Detection Sensors Disbonding/Delamination Sensors

we have eleven technology areas that have high potential to leverage operational capabilities, and we describe these in Section 6 of the Sensors Volume.

Trends and Opportunities

Several trends and opportunities have emerged from this study and call for both near term concrete Air Force actions and long term diligence in developing and exploiting emerging technologies. These trends should be exploited and the opportunities should be pushed forward to gain real benefits. In the following, we summarize the over-arching trends and opportunities along with some illustrative technology examples.

1. Affordable and Enhanced Sensing Through Signal Processing

Many of the advances in sensors that have been achieved recently and will be achieved in the future are directly related to concurrent and supporting improvements in two key areas—computer technology and signal processing algorithms. The exponential growth in computational capacity (ever increasing mega instructions per second [MIPS] per pound, watt, and dollar) is well known. Also important for the advance of sensing systems, but less well publicized, are the dramatic innovations in signal and data processing algorithms, for example, efficient large-array image registration. By exploiting these two key areas, it is possible to shift some of the burden from the sensor itself to the signal/data processor to achieve more affordable and/or enhanced overall sensing systems. This opportunity is often called "trading mass for MIPS" and generally involves using processing power to compensate for inadequacies in sensing hardware.

An example of an important future sensor concept that illustrates this opportunity is "relaxed-optical-tolerance imaging." In the next several decades, the Air Force will have an increased need for fine resolution optical imaging of targets and scenes on a global basis. Using current technology, a space-based optical system with a large aperture would be very heavy to insure structural integrity and rigidity. It would also be expensive and cumbersome to fabricate and deploy. A solution to the current technology shortfall is to relax optical tolerances (thereby reducing weight) on the primary mirror and recover the loss with post detection processing. For example, the primary collector could be a non-rigid (floppy) monolithic or segmented or sparse device involving a very thin mylar surface stretched over skeleton structure. The large aberrations associated with this system would then be overcome with post-detection processing involving algorithms such as *phase-diverse speckle imaging* or *multiframe blind deconvolution*. These algorithms all involve a large number of computations that require on the order of tera-operations for a single million pixel image. The use of new algorithms and advancements in computer technology will allow the development of more affordable and improved imaging systems such as this.

Similarly, signal processing can provide the capability to exploit SAR image data from space or airborne platforms to detect and measure subtle changes in a scene between imaging passes. This technique is often called "coherent change detection" and involves using the phase differences between two SAR images taken with antennas that are displaced either spatially or temporally to retrieve information on motion, change, or surface elevation differences within the images. Differences in phase are indicative of subtle changes between imaging cycles. For example, decorrelation in the image phase indicates changes have occurred in the scene microstructure due to surface disturbances. These changes are usually not observable to a human

viewing the scene nor can changes be seen in a conventional SAR image. This class of sensing techniques will have increasing utility in dealing with many operational tasks of interest to the Air Force in the future.

2. Increasing Use of Multidimensional Phenomenology

A second trend in sensor technology is the growing use of multiple physical phenomena in the sensing process. In addition to the extension to three-dimensional (3-D) spatial imagery, other dimensions can be used as well. Examples include multi, hyper, and ultraspectral (US) optical imaging concepts that use information from a large number of spectral bands. Other concepts combine information from optical and radio frequency bands, from vibration and polarimetry, from reflected spectra, from seismic and RF responses and so on. The common characteristic of these combinations is that they provide additional, often critically discriminating, information about targets of interest, allowing these objects to be detected and characterized with much improved error rates. It has been said that an enemy may hide from us in a few dimensions but not in all dimensions. We must continue to develop and use sensors that involve more and more phenomenological dimensions.

3. Continuing Improvement in Sensor Systems and Component Technologies

Sensors will continue to improve due to developments in enabling technologies as well as in system design. For example, Air Force radar systems are steadily advancing in terms of resolution, ability to penetrate foliage, moving target indication/indicator (MTI) capability, levels of electronic integration, and reliability. Similarly, electro-optical systems boast denser focal planes with broader spectral response, on-chip tunability, and uncooled operation. Inertial systems show steady improvement in drift performance, reductions in size and cost and ever tighter integration with external aids. Supporting electronic components such as A/D converters and embedded signal processors are also improving, becoming faster, smaller and more reliable. These trends will continue and will provide opportunities for improved sensor systems and fundamental changes in the way sensors are designed and used.

One example of new enabling technology described in Section 6 of the Volume is micro-electro-mechanical systems (MEMS). This technology uses material processing methods from the microelectronics industry to make useful structures, including pressure sensors, uncooled IR detectors, bio/chem detectors, accelerometers, gyroscopes, valves, and switches. The distinction is that these devices can be very small (down to lithography scales) and can be mass-manufactured with electronics already integrated, making unit costs potentially very low. Combined with communications and processing, these features enable sensing concepts comprised of many small distributed elements. Such concepts represent a major change of philosophy away from today's larger centralized systems. They also create entirely new sensing possibilities such as micro-sensors for in-situ surveillance and reconnaissance, embedded sensors for autonomous vehicle and aircraft systems, microactuators for adaptive and precision alignment of imaging systems, and microjets for turbulence control over airframes.

Current focal plane array (FPA) technology includes numerous high spatial resolution devices for the ultraviolet (UV) through the Long-Wave IR (LWIR) wavelength range. In general, visible device technology is more mature than that found in the IR. Key IR detector materials are undergoing constant refinement to improve sensitivity. Quantum efficiency (QE) gains have

been secured in PtSi through refinement of the wafer preparation and platinum deposition process and the addition of Fabry-Perot microstructures to the detectors. Notable advances have been made in other materials to reduce detector 1/f noise through improved materials purity and processing techniques. Microscopic lens arrays to increase detector fill factor can also be added. More advanced approaches for FPAs that could lead to dramatic performance improvement include Quantum Well Infrared Photodectors (QWIPS) and strained layer superlattices. These advanced techniques need much development, but could lead to more uniform arrays at long wavelengths and a higher degree of radiation hardness.

Other examples of improvement in sensor systems are related to achieving a nearly continuous observation capability needed for many operational tasks. Continuous observation implies day/night and all-weather operation and suggests the use of microwave imaging sensors. In principle, this could be accomplished by a large number of SAR sensors on LEO satellites or a few in synchronous orbit. The standard type of geo-synchronous satellites have the advantage of continuously seeing a large portion of the earth, but the disadvantage from a SAR point of view is that there is no relative motion to create the synthetic aperture. Previous studies have considered putting the satellite into an inclined orbit, which gives an apparent north/south motion once per day. The drawback to this design is that a fine resolution image requires a significant fraction of a day to collect. The use of Bistatic SAR in which a microwave illuminator is placed in a synchronous orbit with lower orbiting receivers or airborne receivers is an interesting alternative (see SAB Report, "Offboard Sensors to Support Air Combat Operations," April 1992). In this Volume, we describe a low cost space-based surveillance concept involving the use of approximately 10 to 20 LEO satellites for SAR coverage of a theater.

4. Increasing Interconnectivity and Functional Integration

While advances in specific sensor types are important means to achieve required operational capabilities, our analysis has consistently pointed to the power of integrated use of multiple sensors to cope with stressing information gathering situations such as concealed targets. We discuss this subject in the context of a "system of systems" architecture in Section 2. There are both physical and functional dimensions to this integration. On one hand, internetting of sensors through robust, high performance data links to allow coordinated functioning and to rapidly aggregate data at fusion nodes is essential to the basic idea of bringing relevant data from all sources to bear on a given problem. On the other hand, adaptive sensor control algorithms, data fusion, and other information processing functions must be integrated for the available assets to be optimally employed as a single entity.

The subject of sensor correlation and fusion is so fundamental and pervasive that we have devoted all of Section 3 to it. Recognizing that no taxonomy of fusion processes is perfect, we have adopted the four-level model articulated by the Joint Directors of Laboratories and accepted the fact that some important ideas and design principles overlap the levels of this model. Despite decades of research, the state of the art in data fusion is still largely heuristic and the number of actual fielded systems with nontrivial fusion processes is still small. Section 3 of the Volume surveys the many bases on which sensor signatures can, in principle, be combined and highlights the reality that most existing processes come down to multiple hypothesis testing using one or more statistical models chosen on the basis of the data and its known or assumed errors. We again emphasize our recommendation that this is an area where concentrated attention to the underlying mathematical tools would produce major benefits.

Sensor internetting is intimately related to the trend toward higher dimensionality in sensing described earlier. Since it will often be impractical to implement the full range of sensor types needed in a given scenario on a single platform, tight linkages and integrated control become essential to the registration of various target signatures and to adaptive control of individual sensors based on the composite or fused target picture. Internetting is also important as a means to achieve overall robustness in the sensing structure by exploiting inherent redundancies among systems to cope with loss of assets to failures or hostile action.

To make these general ideas more concrete, Table 5 summarizes the seven "illustrative concepts" described in Section 5 of the Volume. These concepts have been chosen to illustrate the ways in which advanced technology can be harnessed in specific system designs to address the improved operational capabilities identified previously. As the table suggests, both improvements in individual sensor species and the trend toward higher levels of functional integration are central to progress in performance and affordability.

Table 5. Examples of Sensor Integration as Part of Illustrative Concepts for Future Systems

Sensor Concept	Example of Improved Sensor Performance	Example of Sensor Integration
UAV Target Reporter	Lightweight, Multimode UAV SAR	Fusion of Multiple Onboard plus Unattended Ground Sensors (UGS)
Internetted UGS	Sensitive, Highly Specific, Passive Chemical Detectors	Area Coverage from Multiple Small UGS of Various Types
Buried Target Surveillance	Microsensors for Covert Penetration of Facilities	Fusion of Seismic, RF, Acoustic and Other Sensor Signatures
Concealed Target Detection	Broadband Low Frequency SAR for Foliage Penetration	Cueing of Fine-Resolution SAR by Wide Area Sensors
Weather Forecasting	Multiwavelength Radar for 3-D Measurement of Clouds, Rain	Fusion of Active and Passive RF and EO Sensors
Multifunction EO Sensor	Optics with No Moving Parts for Low Cost	Multiple Functions Through a Common Aperture
Low Cost Space-Based Surveillance	Multiple Technologies for Light-Weight, Efficient Multimode Radar	Integration of Space and Airborne Surveillance for Affordable Long Term Coverage

5. Rapid Data Exploitation/Automatic Target Recognition

The capability to reliably and automatically recognize sensed visual, IR, and radar images or electronic signatures will provide significant operational benefits to the Air Force in mission areas requiring rapid target identification, intelligence data analysis, battle damage assessment and automatic sensor queing. The state of the art of (spatial) pattern recognition does not yet provide sufficient accuracy or reliability to perform independent and unambiguous automatic target recognition (ATR) for lethal attack in mission applications, but it does provide the ability for rapid screening and automatic sensor cueing (ASC) to support the warfighter.

Classification/recognition algorithms all operate by matching attributes of the measured (unknown) signature with *a priori* information about the potential targets that could be present in the scene. Algorithm technologies differ in terms of the type of information used to match, the way in which the *a priori* information is encoded, and the approach used for matching. The matching algorithm technologies that have been the focus of classification/recognition research fall into four broad categories:

- *Statistical Pattern Recognition*: partitions the space of possible target identities according to target signature attributes.

- *Neural Nets*: models the information flow across components in the human brain to perform the reasoning process that matches pre-stored target features against the unknown to identify it.

- *Template Matching*: codifies the topological structure of the target signatures from a priori data and matches these against the unknown signature to select the most likely identity.

- *Vision*: applies reasoning based incremental signature correspondence between the unknown and the signature properties of all feasible targets to determine the most likely identity of the unknown.

There are basically two fundamental elements required to successfully field ATR/ASC systems. The first and most obvious are the necessary algorithms and processing techniques and methodologies for performing the ATR/ASC function. Physical, quantitative models are required to provide a predictive capability not presently available. There is a need for rigorously derived new models and theories for such models to replace the limited heuristic and ad hoc algorithms, empirical and statistical relationships and human elements currently used for today's problems. The second fundamental element, equally obvious, is the enabling high speed signal or data processing hardware equipment on which the above ATR/ASC algorithms would be performed. Extremely high density storage, rapid onboard access to specialized databases, and extremely high performance computing elements will all be necessary to successfully field robust ATR/ASC systems.

6. Commercial Opportunities

Opportunities to cooperate in the development and utilization of commercial sensing systems are vast. The growing interest in commercial satellite remote sensing systems and plans for collecting fine resolution panchromatic, multispectral (MS), and eventually SAR imagery provide the opportunity to purchase these data for military purposes. The capabilities of these commercial systems need not be duplicated, but rather can serve as part of the overall mix of sensor systems serving the military. Similarly, the development of intelligent, autonomous inspection systems for industrial operations involves a wide variety of sensors and associated recognition systems that are directly related to military applications. Small sensors based on MEMS and surface acoustic wave (SAW) devices are being developed to produce very small, low cost industrial instruments for chemical detection and analysis. These "chemistry lab on a chip" devices have obvious application in counter-proliferation. Another important example is the exploding consumer application of GPS that will provide ever smaller, cheaper receivers for

potential military use. These and many other commercial cooperation opportunities bode well in our quest to field affordable sensor systems.

Recommendations

The Sensors Panel has concentrated on identifying the operationally important enabling technologies for which increased Air Force investment is considered important. These recommendations are contained in the report, and the reader is encouraged to review the entire report in order to grasp the total picture. These efforts will lead to the advent of new technologies and architectures that effectively support the application of air power in the coming decades. Major changes are foreseeable in command, control, communications, and intelligence (C^3I), signal and image processing, ATR and expert systems, providing the potential to acquire a timely and superior knowledge of ourselves and our enemies. Leveraging a tremendously accelerating base of commercial technologies in the digital and computing domain will contribute significantly to these efforts.

Several areas, however, deserve special attention, and the associated recommendations follow. The Air Force should:

1. Establish a central authority to define and control the information architecture, and its sensor segment, as a system of systems

As an overarching recommendation, the Panel believes the Air Force should designate a central authority to define and control overall force structure architecture, specifically the information architecture and its sensor segment. The objective is to halt the proliferation of stovepipe, non-interoperable systems and begin a migration to a "system of systems" architecture that delivers the maximum warfighting effectiveness from the affordable suite of assets. The information architecture should define the requirements levied on individual systems such as sensors and weapons, the interfaces among all elements, and the operating modes through which these assets support dynamic battle command and control. The Air Force should continue the development of systems based on demonstrable technologies such as sensing and data acquisition sensor systems with wholly digital output supported by large-scale networking of these sensor systems supporting "system-of-systems" concepts. Network transport protocols of broad functionality supporting this concept are also needed, with a strong preference for broadly supported commercial standards.

2. Improve multifunction radio frequency apertures

The Air Force should initiate a program, including activities from 6.1 through 6.3, to significantly improve the state of the art in multifunction radio frequency (RF) apertures for radar, radiometry, threat warning and countermeasures (both non-destructive and destructive) and for communication, navigation, and identification (CNI). The basic measure of merit is the product of radiated power, bandwidth, and direct current (DC)-to- RF/RF-baseband conversion efficiency. The goal is technology for affordable RF apertures with multioctave coverage (ultimately operating in selected bands from 1 to 160 GHz), wide instantaneous bandwidth (at least 1 GHz), high radiated power (20 to 100 W) and high efficiency (50 percent across the bandwidth). R&D on RF solid state devices for both transmitter and receiver functions, as well as broadband radiators and high performance signal processing, is central to this program.

3. Improve multifunction electro-optical/infrared modules

Two themes run through our sensor considerations. They are affordability and multidimensionality. Wavelength tuning adds another dimension to our traditional spatial target detection/recognition. Focal plane arrays (with more pixels) and lasers capable of narrow-band tuning over a broad wavelength region are required for expanded multidimensionality. Inexpensive methods of pointing and stabilizing electro-optical systems are required for affordability. Sensitive focal plane arrays that are uncooled or thermo-electric cooled are also required for affordability. The Air Force should initiate a program, including activities from 6.1 through 6.3, to develop multifunction EO apertures for passive target detection, active target location and identification (ID), missile warning and infrared countermeasures (IRCM), and laser communications.

4. Develop a family of air-monitored, unattended ground sensors

UGS offer special promise for a wide range of applications, and the unique abilities of the Air Force to seed as well as read out sensors by aircraft deep in hostile territory suggest a much stronger Air Force UGS technology program. Multiple phenomena (20 or so are obvious to the Panel) and target identification sensing for ground sensors will provide a much better picture of the area under surveillance. No breakthrough in technology is needed to develop a demonstration capability for ground sensing many types of targets. Prototype sensors with advanced signal processing should be fielded to determine the proper mix of sensing elements required to classify various targets. The post-detection processing using fusion with other intelligence to extract and display critical information is the major challenge.

5. Develop a family of micro-sensors for use in airborne, spaceborne, and ground sensor systems

The Air Force should develop a family of microsensors (including MEMS technology) that can be used in airborne, spaceborne and ground sensor systems. This involves monitoring commercial advances in acoustic, seismic, inertial and pressure sensors; testing them for performance in likely military environments (space, jungle, desert); and cataloging suitable sensors for future applications. It also involves developing micro-sensors for specific military unique missions. The most important of these are chemical and biological warfare (BW) agent detectors.

6. Develop tags for air-monitoring the movement of materials and equipments

The Air Force should pursue development of dopant materials which would respond to airborne active and passive sensor systems to reveal the location of the carrier material (chem/bio agents, drugs, raw materials for munitions, etc.). Such dopants might be spectrally identifiable by stimulated or natural fluorescence. Similarly, tagging devices such as optical, infrared, or radio frequency transmitters, retro-reflectors and transponders should be developed to be evident to reconnaissance, surveillance and attack aircraft to locate and track weapons systems, munitions, vehicles, and personnel. Included should be some ability to locate these tags even in foliage and in buildings.

7. Stress sensor affordability through emphasis on revolutionary and evolutionary signal processing concepts

The AF should implement programs for the development of improved algorithms for relaxed tolerance imaging, image compression, ATR, and so forth. Human computer interactions and interface designs for next generation virtual reality displays supporting an "immersive environment" for users should be extracted or modeled from commercial developments in the sensory engineering areas. Robust and quantitative theories and algorithms for effective "system-of-systems" designs optimized for a variety of missions need to be developed.

The rapid improvement in digital technology is recent years allows opportunities to use reduced cost sensor components. We expect that this trend will continue. Digital signal path systems can cost less in both acquisition and life-cycle if sensor technologies and algorithms improve. Additionally, digital systems make possible and practical the design of major systems that will accommodate technological change over several decades (insertion as they become available), thus mitigating technology obsolescence.

8. Exploit the advantages of the multidimensionality offered by multiple sensor regimes

To increase the probability of target detection, recognition, or identification while maintaining a constant false alarm rate (CFAR), one can use a limited number of target dimensions with very high resolution (synthetic aperture radar [SAR] with electro-optical, for example) or increase the number of orthogonal dimensions with limited resolution in any dimension (MTI + SAR + UGS + electronic support measures [ESM], for example).

By expanding the dimensionality of target parameters, more difficult targets can be recognized in clutter/hides and correctly identified. The Air Force should emphasize development of multi and hyperspectral (HS) sensors, combinations of orthogonal dimension sensors such as acoustic with magnetic UGS, and robust fusion/correlation algorithms. Fundamental to the data fusion development is a 6.1 program to formulate a comprehensive mathematical basis for such algorithms.

9. Develop ATR and ASC for sensor systems

ATR and ASC offer very high payoff in improving target identification, reducing latency, greatly lowering data transfer requirements, and simplifying aircrew workload. Major emphasis on the associated technologies, based on further research into the underlying foundations for ATR/ASC, with consideration given to a bio-mimetics processing architecture is needed. Exploitation is required of unattended ground sensor data, moving target indication(s) and both radar and electro-optical/infrared imagery.

Although much needs to be done on next generation capabilities, just as much needs to be done to field in the short term capabilities that exist today. The Air Force should field existing technology systems, however limited, to gain an invaluable set of experiences as they relate not only to technology but to utilization. We can obviously create ideas and concepts for ATR/ASC systems easier than we can employ them. However, valuable experience derived from even limited ATR/ASC systems may conjure up whole new ways of fighting that are not obvious today.

10. Investigate innovative concepts for sensor systems that exploit improved components and integrated operations

The Sensors Panel has identified a number of illustrative sensor system concepts that exploit the advanced technology projections for the purpose of providing significantly persistent wide area surveillance with enhanced target detection and recognition. These concepts are briefly described, along with the attendant technologies, in the Report and include:

- *Target Reporter.* Long endurance unmanned air vehicle with range of air and ground sensor/tag reporting for persistent battlefield surveillance.

- *Integrated Arrays of Distributed Unattended Ground Sensors.* Large areas seeded with multiple micro-sensors implemented on small devices, monitored and processed by aircraft.

- *Underground Target Surveillance.* A system for monitoring underground facilities typically associated with NBC weaponry, leadership centers, and TBM depots.

- *All-Condition Concealed Target Detection.* Exploitation of multiple sensors for the detection of targets under foliage, in camouflage, and in hides.

- *Weather Surveillance and Prediction.* Multiple sensors integrated to provide broad area and local military-unique weather.

- *Modular, Integrated, Multifunction Phased Array Based Electro-Optical System.* Affordable and robust, multiaperture defensive and attack processing.

- *Low Cost Space-Based Surveillance.* A mix of high resolution radar and imaging electro-optical sensors on small, launch-on-demand satellites.

The picture which emerges from these concepts is that of a feasible, affordable approach to greatly enhanced information gathering in the battlespace through a combination of advances in individual sensor technologies and, especially, processing for cooperative sensor operations.

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1.0 Introduction

Sensors provide data and information which lead to increased knowledge about various physical phenomena, materials, and objects of importance to the military. Knowing more and knowing it sooner than the enemy provides an advantage and motivates the goal of acquiring "near perfect" knowledge of the battlefield as well as overall global situation awareness at any time and under any weather condition. This is a key challenge for the Air Force. The often cited explosive change in the field of information technology provides the solution to this challenge and with expected developments in technology over the next 20 years, the goal of information dominance is realistically achievable.

From a military point of view, the task of dealing with information is often treated in terms of four main functions: (1) information collection, (2) information transport, (3) information management/decision making, and (4) information protection and denial. Sensors are an important part of this much larger information and weapon system and primarily serve the information collection function. They must operate in concert with other elements and within the constraints of the overall system including very short reaction timelines for some weapon applications.

Sensors represent a very broad class of measurement systems. As will be described in more detail later in this Volume, sensors can exploit the full electromagnetic spectrum, detect various forms of mechanical energy, for example, seismic and acoustic, and physically sample and analyze a diverse set of chemical and biological components. Moreover, sensor systems can be operated from a variety of platforms in space, in the air, on the surface or below the surface of the earth. The sensors can be operated from stationary or moving vehicles that can be inhabited or not. Indeed, many of the sensors of the future will be transported by mechanical crawling roach or flying bumblebee-like devices.

Applications of sensors are also extremely diverse. In addition to the notion of real-time, global knowledge (omnipresence), sensors have a host of traditional roles including targeting, threat warning, battle damage assessment, flight weather forecasting, and monitoring of clandestine manufacturing. One key military goal is related to denying a sanctuary for the enemy. This motivates the development of radar systems that can image buried targets or targets concealed by foliage. Similarly, laser sensors for detecting and analyzing vibrations and effluents from underground facilities are important as part of an overall approach to counter-proliferation. Sensor systems for these and other challenging military needs will be discussed in subsequent sections of this Volume.

In the future, we will continue to move from centralized and independently operated sensors to large arrays of sensors in space, on high altitude UAVs, and distributed miniature sensors and tagging devices that are internetted and operated in an integrated fashion. Some of these sensor concepts involve distributing the small component sensors (flying, crawling, or fixed-implanted) by means of LO aircraft or by special operations forces in some situations. The use of distributed and coordinated arrays of small sensors is one way to improve overall performance while increasing survivability and reducing cost.

Sensors are an essential element of virtually every Air Force weapon and support system. The hardware and software associated with sensing functions are generally major, and sometimes predominant contributors to the performance, reliability, supportability, and cost of such systems. Many of the technologies associated with sensors are in a state of rapid evolution and will

remain so for the foreseeable future. Moreover, many sensing functions and devices that are important to the Air Force have counterparts in commercial and industrial applications. This combination of ubiquity, operational impact, technology leverage, and dual use potential makes the subject of sensors especially important to the themes of *New World Vistas*.

Opportunities to cooperate in the development and utilization of commercial sensing systems are vast. The growing interest in commercial satellite remote sensing systems and plans for collecting fine resolution panchromatic, multispectral, and eventually synthetic aperture radar imagery provide the opportunity to purchase these data for military purposes. The capabilities of these commercial systems need not be duplicated, but rather can serve as part of the overall mix of sensor systems serving the military. Similarly, the development of intelligent, autonomous inspection systems for industrial operations involves a wide variety of sensors and associated recognition systems that are directly related to military applications. Small sensors based on MEMS and SAW devices are being developed to produce very small, low cost industrial instruments for chemical detection and analysis. These "chemistry lab on a chip" devices have obvious application in counter-proliferation. These and many other commercial cooperation opportunities bode well in our quest to field affordable sensor systems.

In concert with the *New World Vistas* theme of "identifying fields of rapid technological change that are likely to revolutionize the 21st century," the objective of this Volume is to describe new sensor concepts and technologies which, if pursued, will have strong impact in satisfying important military needs in the future in terms of greatly improved performance and/ or affordability. Opportunities to cooperate with commercial developments and dual use implications are also important factors in identifying the key sensor concepts and technologies to be pursued.

The Sensors Panel followed a dual path approach during the course of this study leading to the information presented in this Volume. One path of the approach involved studying representative operational military tasks and then determining significant challenges for sensors of the future. We then identified future sensor concepts and enabling technologies to satisfy these needs. As a parallel path, we also reviewed a sample of current sensor technology development activities occurring in industrial, university, and government laboratories and finally selected those sensor technologies that we judged to have the greatest military impact.

In order to set the stage for a description of sensor concepts and enabling technologies, it is important to define the steps in the general sensing process, including the basic step of transduction as well as steps related to signature extraction, assessment (location, tracking, classification, correlation), and interactions with users, other sensors, and stored data. Section 2 describes this **sensing process** from a broad point of view in order to avoid conventional constraints on our thinking and to motivate a fundamental and comprehensive examination of sensor needs and approaches to satisfy those needs. This section also provides a taxonomy of sensors and sensor architectural considerations to be used as a context for subsequent portions of this Volume.

In most sensing situations, improved performance in terms of increased confidence in decisions and improved system reliability and availability can be achieved by combining data from multiple sensors or combining time-sequenced measurements from a single sensor. This combining of data to increase the temporal, spatial, and spectral dimensionality of the sensing

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process is often called "**sensor correlation and fusion**" and is the subject of Section 3 of this Volume. The basic data fusion process is defined along with a description of the various categories of data fusion. The section concludes with a summary of important challenges and opportunities that are associated with sensor correlation and fusion.

Section 4 presents a description of seven **representative operational tasks** associated with key Air Force missions and a set of challenging sensor needs derived from these tasks, and indicates some future sensor concepts and related enabling technologies that would satisfy these needs. This top down approach was taken to generate stressing needs for sensors and to stimulate the identification of new sensor concepts.

The development of new improved sensor system concepts can occur due to improvements in components and basic design approaches. Another very effective approach involves the integration of multiple sensors to achieve improved overall performance through cooperative operation of an internetted set of orchestrated sensors. Seven **illustrative sensor system concepts** are described in Section 5. These concepts were selected to indicate the power of integrated sensor operation and the enabling technologies needed for implementation.

Section 6 describes the **sensor technology** that we believe will be important for the Air Force in the coming decades. This description emphasizes areas where we expect substantial change from current practice and also discusses developments that can be expected from commercial efforts. The technology areas considered in this section are derived from the enabling technologies identified in Sections 4 and 5 and from other technology development activities that we believe offer opportunities for the Air Force.

Finally, **conclusions and recommendations** prepared by the Sensors Panel of *New World Vistas* are presented in Section 7 of this Volume. The conclusions portion summarizes several over-arching trends and opportunities that have emerged from this study, and the recommendations portion of this section identifies a set of specific actions that the Air Force should take over the next few years to exploit the trends and opportunities to gain real benefit in the future.

2.0 The Sensing Process

2.1 Introduction

In order to escape the constraints of conventional thinking about the preferred approaches to implementing various sensing functions, we take a very broad and generalized point of view. The operation of a sensor necessarily entails: (1) the exploitation of one or more physical phenomena that convey information about the external environment (sensing domain), (2) use of hardware and software designed to interact with the sensing domain and with the people or machines to which the sensor provides information, and (3) schemes for producing, storing, and manipulating the information that the sensor yields. However, in almost every sensing situation there will be multiple choices in each of these categories, and the approaches suggested by conventional wisdom may not be optimal. This is especially true as affordability comes to equal or exceed performance as the driving priority in many systems. The very different taskings that the Air Force confronts in the post-Cold War era are likely to require different sensing capabilities, and this raises questions about the adequacy and appropriateness of the current system inventory. Moreover, advances in technology increasingly create opportunities to share a given set of sensor assets among multiple functions and to coordinate the operations of individual sensors in ways that produce significant operational benefits. All of these considerations motivate a fundamental and comprehensive examination of sensor requirements, the best ways to approach them, and opportunities to improve system capabilities while controlling costs of acquisition and ownership.

2.2 The Sensing Process

Figure 2-1 graphically represents the steps that are present in any sensing process. The underlying phenomena can be as diverse as intercepting reflected or naturally occurring electromagnetic (EM) radiation, detecting seismic or acoustic energy, trapping chemical or biological agents, or measuring the motion of the sensor's platform. We define an active sensor as one that stimulates its external environment and measures a reflection or other response and a passive sensor as one that does not.

2.2.1 Transduction

The sensor proper starts with some means of converting the stimulus of the sensed phenomenon into a signal or data stream that information processing hardware and software can manipulate. Familiar transducers include antennas connected to RF front ends, electro-optical (EO) detectors with associated optics, microphones and seismographs, and the accelerometers and gyroscopes used in inertial navigation (NAV). As suggested in Figure 2-1, multiple apertures of the same or different types may be used to achieve the required field of regard or because multiple phenomenologies are used. In every case with which this volume is concerned, the output of the transducer will ultimately be in the form of an analog electronic signal or a digital data stream. However, at intermediate stages of the process, the sensor's content may take the form of charge packets (e.g., charge-coupled device [CCD] readout from a focal plane array), optical energy (e.g., optical filtering or Fourier transform), acoustic energy (e.g., frequency determination using a Bragg cell), mechanical vibration (e.g., resonant gyroscope), or, presumably, some other form of energy. The transducer will normally operate on the raw collected content to achieve amplification, rejection of spurious or uninteresting

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content (filtering), or other "signal conditioning." In addition, the transducer will generally be controlled in sensitivity, bandwidth, or other parameters to maximize its ability to sense things of interest while rejecting other stimuli. It is now general practice to perform analog-to-digital conversion (ADC) early in the sensing process to minimize corruption by noise and interference. Ultimately, this stage of the process produces as output one or more signals or digital data streams.
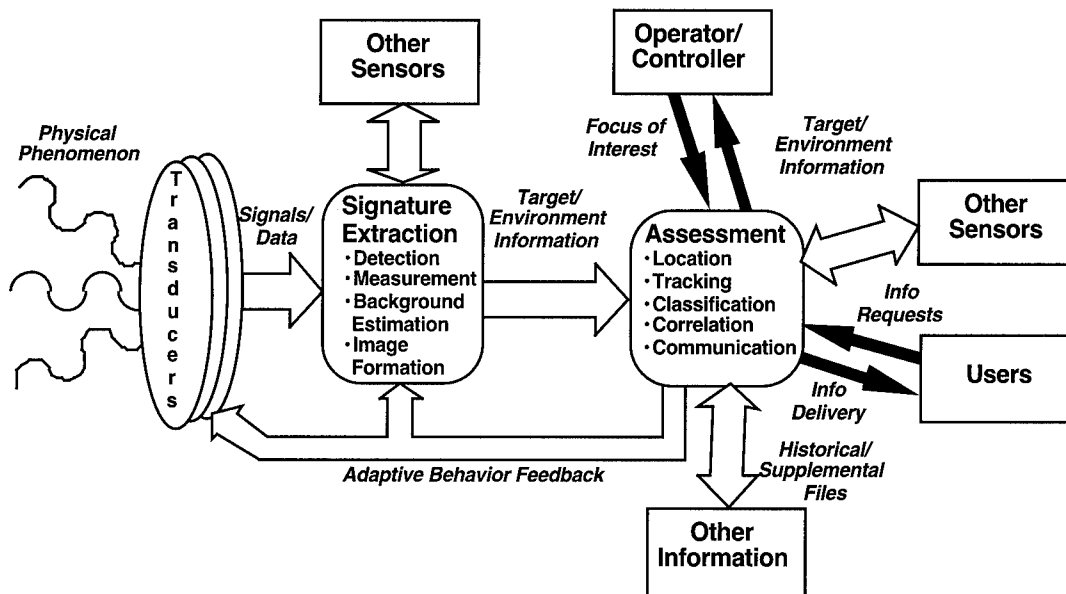
Figure 2-1. Elements of a Generalized Sensing Process

2.2.2 Signature Extraction

The next stage of the sensing process operates on transducer output to determine its content. This may be as simple as declaring that a given signal or data pattern represents a target (e.g., has an amplitude higher than a preset threshold) or may involve a more complex measurement of parameters such as intercepted signal frequency, Doppler shift, time dependent amplitude, and so forth. We denote any object of interest in the sensing domain as a "target" regardless of whether hostile intent is involved. Depending on the nature of the sensor, the bearing and range from sensor to target may be available from pointing angle and round trip time delay, or the signal may be associated with a broad sector of the environment. Sophisticated processing such as MTI and spatial/temporal filtering may be used to extract valid targets from noise or background clutter. Many sensors, for example, synthetic aperture radars, require a significant amount of processing to form (reconstitute) images from the raw collected data. In addition, it may be important to sample and determine aspects of the environment such as the statistics of the noise and clutter background seen by the sensor. As shown in Figure 1, the assessment process may be fed by data from other cooperating sensors in addition to that coming from the system's own transducers. In short, this stage converts transducer and contributing sensor data into information about the sensing domain and objects in it.

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2.2.3 Assessment

In a simple sensor system like a first generation radar, all that may remain is to display the detected information to an operator. More generally, the result of signature extraction becomes the input to a more elaborate stage of processing in which information is assessed over time to develop a more complete information base on the sensing domain. Typical examples include:

- Integrating individual target locations over time to reduce the effects of system errors and noise.

- Developing a track for a moving target.

- Evaluating current and historical information to classify a target (e.g., as friendly or hostile or as a specific type or model of vehicle, ship, aircraft, etc.).

- Correlating information from more than one sensor or other information source first to determine that a common target is involved and second to combine the information to improve the system's knowledge of that target.

- Determining that a given body of data is of interest to other systems or users and communicating accordingly, for example, to cue a different sensor to seek a given target.

2.2.4 Interactions

A single function, unattended sensor may be entirely self contained and have no external interactions other than perhaps a data channel to pass along its findings. Most sensors, however, have some or all of the interactions shown in Figure 1.

- **Users.** The ultimate purpose of a sensor system is to deliver information to an operational user—from individual warfighters to national command authorities. Users place requests for required information, and the system initiates and reports the corresponding information collection and analysis activities.

- **Operators and Controllers.** In general, a system will function under the immediate control of an operator or programmed controller. The control authority inputs the search parameters, target types, or other data defining the focus of attention that the sensor is to address and monitors sensor output.

- **Other Sensors.** In addition to the previously described possibility that cooperating sensors may feed data to the signature extraction process, information on targets and environments derived from assessment processing may be shared. This is discussed in more detail under the sensor data fusion topic in Section 3.

- **Stored Information.** Finally, the assessment function may use historical data or other information that is not registered in time and space with the immediate targets of interest. Attribute files may be used to associate new target locations with earlier detections of the same targets, or intelligence data may contribute to target identification. For example, a track history from takeoff may be the best source of non-cooperative target recognition (NCTR) for an unknown aircraft.

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2.2.5 Adaptive Behavior

The effectiveness of a sensor can be greatly enhanced through constant adjustment of the transduction and signature extraction stages based on the results of processing target and environment information. Detection thresholds, operating frequency or bandwidth, filtering, and other characteristics may be controlled based on operator or user inputs, clutter and false alarm statistics, and other measures of performance.

2.3 A General Model

The process in Figure 2-1 can, with great generality, be mapped onto a functional sensor structure like that shown in Figure 2-2. The aperture interacts with the environment to convert the phenomenology being used into a suitable form of energy. In an active sensor, the aperture also includes the transmitter, which may be a discrete function like a laser or a distributed implementation like the power sources in the transmit/receive (T/R) modules of an active electronically scanned array (AESA). Virtually any sensor has electronics close to or integral with the aperture to detect, amplify, filter, or otherwise condition the aperture signals. Examples include use of charge coupled devices to collect and time integrate the carriers generated in a focal plane array, a low noise amplifier/mixer chain in an RF front end, and a force rebalancing loop for a gyroscope. In any modern sensor, the aperture output will be analog-to-digital converted and passed to a digital processor for signal and data processing. These functions may be centralized for an entire platform or distributed to individual sensors or both. In any case, the types of processing and interactions described in the preceding section occur here.
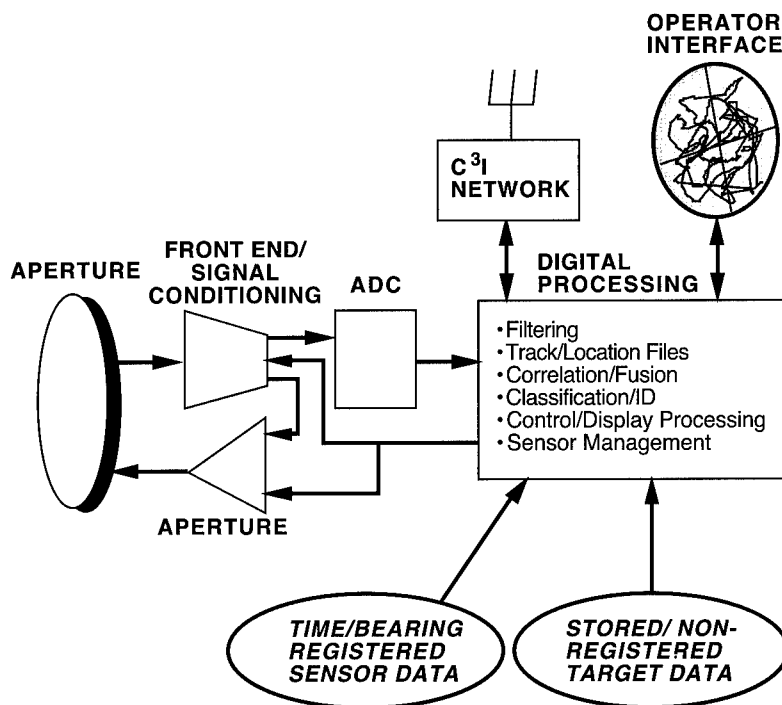
Figure 2-2. Generalized Functional Model of a Sensor

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Commonly, the operation of the aperture will be adjusted in real or near-real time based on both the instantaneous attributes of aperture output and commands generated by the processor or entered by a system operator. Such adjustments might include resetting a detection threshold, changing sensor scan volume, changing transmitter power, and so forth. For example, a signal intercept receiver might be commanded to dwell in a specific frequency bin to confirm the presence of a threat signal based on a tentative match by the processor of a received signal to a threat library. Figure 2-2 makes explicit the distinction between two classes of supporting information. Sensor inputs that are to be correlated or fused in near-real time must be registered both spatially and temporally so that the processor can unambiguously associate individual information streams with a common target. Historical files and other *a priori* data may include spatial coordinates, target attribute lists, or other information to allow association with real-time targets.

2.4 Sensor Taxonomies

Sensors can be classified in many ways to facilitate an orderly discussion of this exceptionally diverse subject. The two most relevant for the present discussion differentiate sensors on the basis of the exploited physical phenomena and the operational tasks supported.

2.4.1 Sensors Classified by Phenomenology

In Table 2-1, sensor types in each area of phenomenology are further broken out by active and passive types and, in some cases, by advanced types that extend basic sensing modalities. Typical sensor types are listed, but the table is not exhaustive; only types of primary Air Force interest are included.

2.4.2 Sensors Classified by Operational Use

Next, we consider typical operational tasks which require sensing and typical sensors used for each. These applications are indicated in Table 2-2. Most applications can, in principle, be addressed with more than one type of sensor, and considerations of affordability, reliability, flexibility (support for multiple missions and tasks) and ability to contribute to an overall picture derived from multiple individual sensors become important in defining an optimum sensor system inventory.

A further classification of significance is the platform on which a sensor will be carried, since considerations such as weight, endurance, available power, and engagement dynamics may greatly affect the achievable level of sensing performance and the optimum choice of sensor type(s). This is most dramatic in the case of space-based sensors, where severe weight and power limitations combined with relatively short viewing windows (for low earth orbit) or very long ranges (for geosynchronous orbit) dictate very different sensor designs from airborne or ground based systems. Thus, in the past, EO sensors have been the primary choice for space-based wide area surveillance, despite their inability to see through clouds, because they are small and light compared to an active RF sensor. This is changing rapidly as imaging radar technology is developed.

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Table 2-1. Phenomenology Classification

Physical Phenomenon	Active Sensor Types	Passive Sensor Types	Extended Sensor Concepts
Electromagnetic • DC/Low Frequency		Bistatic radar, conductivity meter	Advanced unintentional RF illumination sensor
• RF Wavelengths (RF, microwave, mm wave)	Radar, IFF I/T	CNI, radiometer, RWR, ESM	Passive imaging radiometry
• EO Wavelengths (IR, visible, UV)	LADAR, LIDAR [1]	Spot tracker (IRST, MLW), imager (FLIR, NVG, FPA)	Multi or hyperspectral imagers
Mechanical • Acoustic	Ultrasonic NDI	Microphone	UGS
• Seismic	"Thumper"	Seismograph	UGS
• Inertial		Gyroscope, accelerometer	
Chemical/Biological	Trained organisms	Permeable membrane, spectrometer, chemical reaction	UGS

2.5 Challenges and Opportunities

As noted in the Introduction, the radically different military environment confronting the Air Force creates new and different requirements for sensor capabilities. Two examples of the operational challenges that will stress Air Force sensor systems are the "expeditionary force" posture that requires CONUS-based forces to be deployable almost anywhere on earth, ready to fight on arrival, and the prominence of low-level conflict and operations-other-than-war. Both of these place stress on the ability to rapidly collect large amounts of information about an area of operations with limited on-the-ground access. Constraints on the numbers and costs of sensing systems mean that platforms and sensors must have great mission flexibility and high levels of autonomy. Both evolutionary and revolutionary improvements in sensors are likely to be essential in meeting these challenges.

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1. In keeping with common practice, we label an active EO sensor used to detect and track "hard" body targets as a LADAR and one used to sense the presence of clouds, gases, or other diffuse targets as a LIDAR.

Table 2-2. Applications Classification

Sensor Applications	Typical Sensor Types
Wide Area Surveillance	Radar (AWACS, Joint STARS, OTH, etc.), Passive EO Imaging, SIGINT
Threat Warning	Passive EO (missile launch detection/approach warning), RWR, CNI/ESM, SIGINT, Radar
Reconnaissance/Battle Damage Assessment	Imaging EO, Imaging Radar, ESM, Fire Control Sensors
Air-to-Air Detection, Tracking, & Fire Control	Radar, IRST, ESM (e.g., ARM seeker)
Air-to-Ground Targeting & Fire Control	Radar (SAR), FLIR, LADAR, ESM
Missile Guidance	Inertial, Stellar, GPS, Radar, LADAR, Passive EO, ESM, Beam Rider, Proximity Fuze
Navigation	Inertial, GPS, Imaging Radar, Stellar, CNI
NBC Detection	Specialized Detectors, DIAL, Hyperspectroscopy, LIDAR
Ground Traffic	Acoustic, Seismic, including UGS
Weather	Radiosondes, Doppler Radar, Imaging EO, LIDAR
Science and Technology	Imaging EO and Radar, ESM/SIGINT
General Intelligence and Indications and Warning	ESM/SIGINT, Imaging EO and Radar, Wire Taps, Acoustic/Seismic, UGS
Medical/Crew Health Monitoring	Multiple Biomedical Instruments
System Health Monitoring	TSMD, Built-In Fault Detection/Isolation, NDI

We begin with several overall "grand challenges" which affect the area of sensors in general. Later discussions will focus on specific challenges associated with representative operational tasks. Among the grand challenges confronting sensor system designers and users are:

2.5.1 Data Rates and Volumes

A pervasive theme is the fact that technological advances in sensing apertures and phenomenology have created a situation in which our ability to collect raw data significantly exceeds our ability to extract useful information from that data. A high resolution (10^6 pixel) spaceborne imaging sensor in low earth orbit that collects 10 images over an area of interest per pass with 10 bits of gray scale data per pixel would dump 100 Mbits of data into a theater C^3I network every 90 minutes. Multiple sensors of various types easily take the input data flood to many Gbits. The great majority of this can be expected to be routine background of no interest to the warfighter, but the small percentage of valuable content on forces, targets, defenses, and so forth. must be separated out, characterized, and disseminated in near real time. This is one of the key points of tangency between the domains of sensing and information processing. Among the implications of this huge data volume are:

- The need for very high speed representation, storage, and retrieval of enormous data files.

- The need for efficient, fast indexing techniques to allow rapid sorting and processing of selected data contents.

- The need for means of reconciliation among distributed databases to ensure consistency and accuracy, referred to here as "truth maintenance."

2.5.2 Improved Sensor Performance

Growing needs for sensor-derived information, coupled with limited numbers of systems in the affordable force structure, create ever-growing demands on the performance of sensors of all types. Examples of these challenges include:

- The need for precise registration, both spatial and temporal, of individual target signatures both for accurate location and track determination and to support correlation and fusion of outputs from multiple sensors.

- The need for calibration of the sensor itself and of its output, including continuous adjustment of apertures and processors to maintain accuracy, coordinate conversion and orthorectification of target data, and continuous measurement of clutter, false alarms, and other environmental parameters to assess the quality of target signatures.

- The need for greater sensitivity and discrimination, especially as demands increase for detection of small targets in highly cluttered backgrounds.

2.5.3 Improved Asset Management

Another pervasive theme of this analysis is the importance of using all available sensing assets in a fashion that delivers the greatest support to decision makers and warfighters. Once again, this involves the ill-defined boundaries among the domains of sensing, communications, and information processing. Among the specific challenges are:

- The need for an architectural hierarchy which allows timely sharing and use of information, both to use sensor outputs to meet operational needs and to optimize sensor operation based on customer priorities.

- The need for coordinated control of similar and dissimilar sensors, both to employ available assets in a way that delivers the greatest possible information value to customers and to facilitate reconciliation and correlation of multiple target detections and tracks.

We seek both opportunities to improve existing sensor technologies and areas where new and different approaches are required. An example of the latter might be to move away from the familiar picture of a sensor as a relatively large, expensive and powerful device toward a concept of "pervasive sensing" in which huge numbers of small, cheap devices saturate a sensing domain.

Table 2-3 lists several generic characteristics which apply to virtually any sensor system. Specific operational sensing tasks and the associated technologies and challenges are discussed

in detail later in this Volume. However, before considering individual operational situations, it will be helpful to provide an architectural framework for thinking about sensors in the context of an overall force structure.

Table 2-3. Sensor Characteristics and Related Benefits

Characteristics	Operational Benefits
Higher Degrees of Dimensionality [2]	• Improved Target Discrimination • Enhanced Countermeasure Resistance
Adaptive Behavior	• Enhanced Clutter Rejection & Countermeasure Resistance • Enhanced Operator-System Interaction
Data Fusion	• Enhanced Target Detection/Classification/Identification • Redundancy in Critical Functions

2.6 Architectural Considerations

As the discussion thus far has suggested, individual sensors are increasingly employed as elements of an overall force structure in which many systems participate cooperatively in surveillance and intelligence gathering, target detection and tracking, fire control (FC), battle damage assessment, and so forth. Thus, while specific actions like locking up a target with a fighter's radar to launch a missile are focused narrowly on a single sensor, the engagement as a whole is likely to include inputs to the commander, weapon controller, and shooter from many other sensors which facilitate target location and identification, threat avoidance, and other aspects of a successful mission. Furthermore, the ability to combine information from onboard and offboard sources is widely held to be a significant means of cost containment in future weapon systems. It is therefore increasingly vital that sensors be specified, developed, and used with a clear understanding of the interfaces and shared functions that they will encounter as nodes in the force structure architecture.

Figure 2-3 suggests the major segments of a theater conflict force structure (ground, air and spaceborne) and the fact that any system in any segment may need to communicate with any other. An operation of smaller scope might not involve all these assets, but the general principles are the same. The airborne segment is divided into three subsegments to reflect the practical differences between high value standoff platforms such as Joint STARS, AWACS, and ABCCC, the growing significance of UAVs that overfly hostile territory, and the continuing importance of manned fighter and attack aircraft and their weapons. Although the full elaboration of this notional architecture is beyond the scope of this Volume, several aspects must be effectively dealt with if sensors are to make their full contribution to force effectiveness.

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2. We use this term to denote expansion of the sensor variable space, for example, by adding time, spectral regions, or other phenomenologies to the list of things that are measured, tracked, and analyzed in order to improve sensitivity and discrimination.
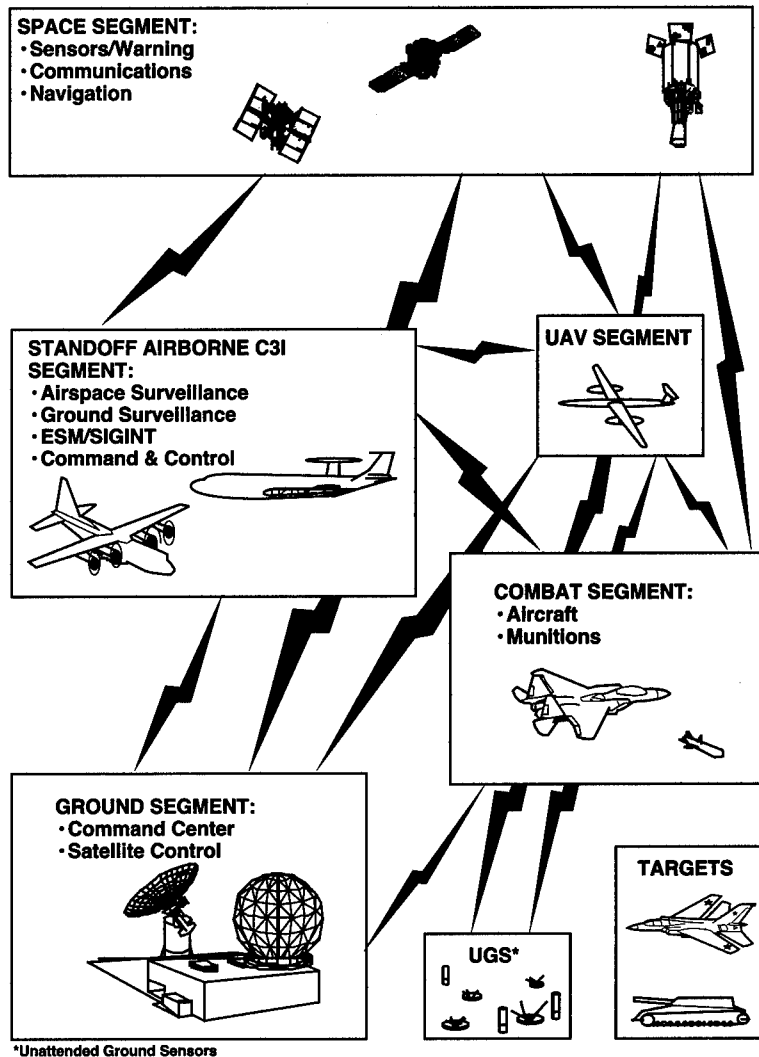
Figure 2-3. Elements of a Force Structure Architecture With Multiple Sensor Systems

2.6.1 Requirements Allocation

A cost-effective force structure demands that individual platforms and sensors be defined in a system-of-systems context that optimizes overall functionality while avoiding over- or under-specification of individual systems. An important consideration here is a combination of complementarity and orthogonality in the set of sensors that addresses a given operational task. *Complementary* sensors exploit the same phenomenology to provide target information from various vantage points in space and time, allowing a more complete and accurate signature. *Orthogonal* sensors exploit differing phenomenologies to derive more information about a target. Orthogonality is one aspect of the use of higher orders of dimensionality, and this and the other concepts in Table 2-3 are important in requirements allocation decisions.

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2.6.2 Internetting

In order for an array of sensor assets to function as a single, coordinated entity, communication channels for data, imagery, voice, and other traffic involved in the operations of the architecture must have the capacity, robustness (including jamming and interception resistance), and interoperability (which implies standardization) to allow the necessary near-real time interchanges of data and commands. Command and data links can easily range from a few hundred bits/second to many gigabits/second.

2.6.3 Cooperative Sensor Functions

As discussed in more detail elsewhere in this Volume, sensor fusion and efficient, timely interaction with operational customers are critical to the support sensors deliver to warfighters. A properly designed force structure architecture provides for cooperative functioning among sensors and with commanders, controllers, shooters, and other users. That architecture must provide for distributed processing of sensor information and for cooperative management of sensor assets.

2.6.4 Global Conventions

For effective management of assets, especially correlation and fusion of sensor outputs, all systems must speak a common language of coordinates, timing, status reporting, communications protocols, and other universal attributes. Standardization of ground control stations, constellation management, hardware and software configuration items, and other aspects has great potential for reducing the costs of acquisition and ownership, especially of space-based systems.

2.7 Summary

The overall subject of sensors is exceptionally diverse, both in the range of physical phenomena available and in the array of difficult information gathering requirements that sensors must address. Sensors are challenged to deliver comprehensive, precise information about many kinds of objects and activities over very wide areas in near-real time, and to do so with assets that are affordable and robust in the face of hostile countermeasures. The key to meeting this challenge lies in the use of a carefully orchestrated array of sensors, from geosynchronous orbit to embedded in the earth, which operate cooperatively and whose outputs are combined and analyzed to extract the greatest level of useful information. The elements of this sensor architecture have been sketched in this section. The sections which follow expand on specific technical and operational aspects.

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3.0 The Sensor Correlation and Fusion Process

3.1 Introduction

For many Air Force weapon and support systems employing sensors, performance requirements can be met only when data from multiple sensors or time sequenced measurements from a single sensor are combined. This process of combining data has been called sensor correlation and fusion, or simply data fusion. As the performance requirements increase (e.g., the demand for higher detection performance at lower false alarm rates) and targets become more difficult to sense (e.g., low observability), there is a greater demand to expand the dimensionality of sensed information acquired—driving the need for multiple sensors and the combination of that data. This demand to expand the time and space dimensionality of sensed data adds two important themes to *New World Vistas*: (1) sensors must be designed to be integrated and coordinated to maximize the overall system measurement process, and (2) processes are required to efficiently and accurately correlate and fuse data from a variety of sensors.

For purposes of this report, data fusion is defined as follows:

Data fusion is a multilevel, multifaceted process dealing with the registration, detection, association, correlation, and combination of data and information from multiple sources to achieve refined state and identity estimation, and complete and timely assessments of situation (including threats and opportunities). (Based on the standard definition developed by the Department of Defense [DoD] Joint Directors of Laboratories)

Sensors produce individual observations or measurements (raw data) that must be placed in proper context first to create organized data sets (information) and then evaluated to infer higher-level meaning about the overall content in the information (knowledge). Consider, for example, a data fusion system that combines SAR and hyperspectral (HS) data. The SAR and HS sensors produce time-sampled data. The SAR data is processed to form an image, and the HS data is processed to form multilayer imagery: these images are registered and combined to produce information in the form of an image database. The image database is evaluated to infer the presence of transportation networks, facilities and targets; this is the knowledge (or intelligence) that is sought by the warfighter.

3.2 The Data Fusion Process

Notice that the data fusion process includes functions normally considered to be included within individual sensor pre-processing and even encompasses the functions traditionally included within single sensor ATR. These functions, enumerated within the definition above, include:

- **Registration.** Registration (or alignment) is the process that places all sensor data in a common time and space coordinate system. This corrects for the different time sampling, viewing perspective and image planes of different sensors.

- **Detection.** The decision regarding the presence or absence of an entity (e.g., target or aggregate of targets) or event (e.g., missile launch) may be based upon the evaluation of multiple individual sensor decisions, or it may be based upon

the combination of raw data from multiple sensors (often referred to as pre-detection fusion).

- **Correlation and Association**. The process of fusion which partitions data into associated categories (also referred to as labeling) includes correlation and association stages. In a typical problem, the data from different sensors are partitioned to associate all measurements from common targets into individual target categories. Sensor measurements are compared with correlation metrics that use temporal, spectral or spatial properties to score each alternative assignment hypothesis. The sensor data are then associated with the corresponding data from other sensors and are assigned to categories (e.g., track files, targets, entities, events).

- **Combination**. The process of combining data from all sensors to derive a refined estimate of state and identity must manage the uncertainty in sensor measurements and provide estimates with associated measures of estimate uncertainty.

- **State and Identity Estimation**. The output product from the data fusion process includes estimates of state (kinematic behavior, often in the form of a track file including track history and a state model to predict short term dynamic behavior) and identity of the entity or event.

- **Assessments of Situation and Threats**. At a higher level of abstraction, the process also evaluates the meaning of the data to assess the situation, including potential threats (defensive) and opportunities (offensive). This process incorporates intelligent reasoning functions including iterative search operations to assess the meaning of entire data sets at the highest level of abstraction.

3.3 Categories of Data Fusion

Four categories of data fusion application that must be mastered to achieve the objectives of *New World Vistas* include:

- **Target Data Fusion**. The fusion of point target data from multiple co-located or dispersed sensors to develop target state (tracks) and identities for C^4I systems.

- **Multisensor ATR Data Fusion**. The fusion of imaging (two-dimensional) and non-imaging data to perform automatic target recognition.

- **Image Data Fusion**. The fusion of multiple sources of image (two-dimensional) and non-image data to generate enhanced image products that present the full information content from all sources.

- **Spatial Data Fusion**. The fusion of more general spatial data (three-dimensional representations of real-world surfaces and objects that are imaged) combines multiple data views into a composite set incorporating the best attributes of all contributors.

This paper describes the motivations for sensor fusion before defining both image and spatial data fusion as a subset of the more general fusion process. Then, the state of the art in three major application areas is described.

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The taxonomy in Figure 3-1 illustrates the functions of each form of data fusion and the distinctions between the output products for each of the four.

These four categories are required throughout the seven representative operational tasks of the *New World Vistas*, as demonstrated in Table 3-1.
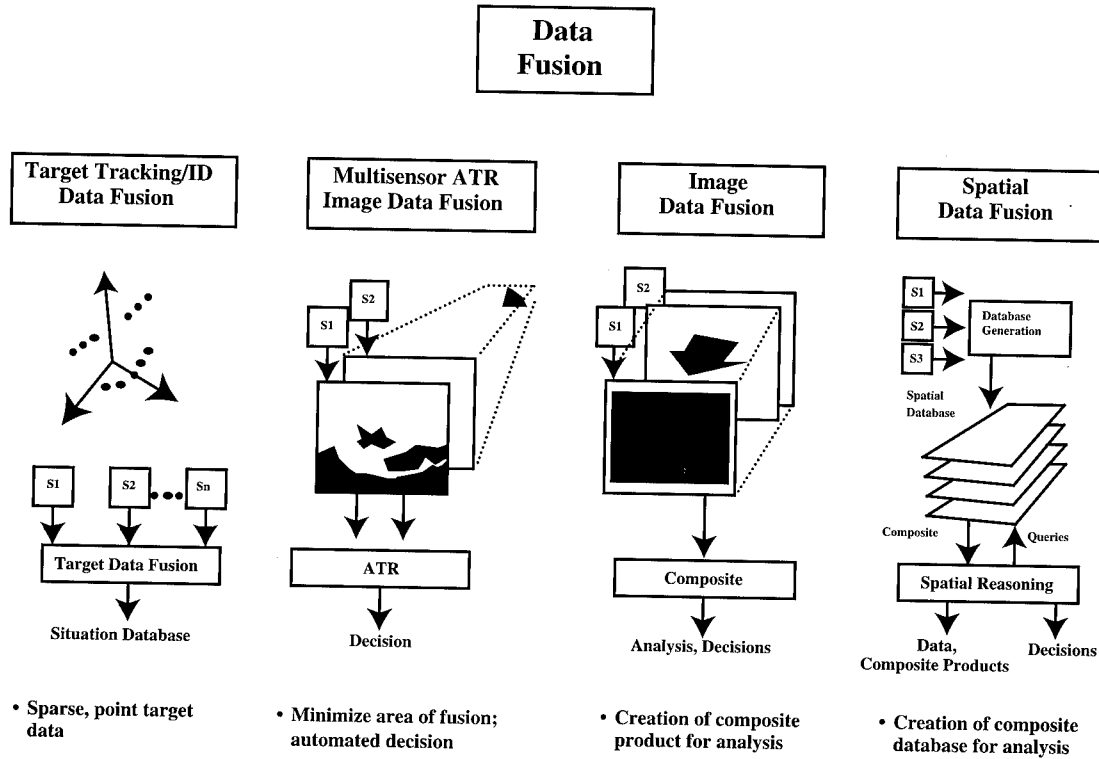
Figure 3-1. Four Categories of Data Fusion are Required for New World Vistas

Table 3-1. Representative Roles of the Four Categories of Data Fusion Across the Seven Air Force Operational Task Areas

Operational Tasks	Target Data Fusion	Multisensor ATR	Image Data Fusion	Spatial Data Fusion
1. Real-Time Situation Awareness	Target Tracking and ID	Non-Cooperative Target ID, Recognition	Surveillance Imagery Enhancement	Terrain Visualization, Planning
2. Global NBC Capability Surveillance	Equipment, materials Detection, tracking	Equipment, Materials ID	Surveillance Imagery Enhancement	Facility Visualization
3. Hardened/ Underground Facility Surveillance			SAR/HS Detection	
4. Recon and Deliver Weapons to Air-Ground Targets	Netted Target Tracking	Non-Cooperative, Lethal Target Recognition	Target Map Generation	Ground Target Precise Geo-Location
5. Detect, Track, Intercept Theater Ballistic Missiles	Detect and Track Via Air, Ground, Space Sensors	Radar/IR/LADAR Missile Typing		
6. Acquire, Maintain, Disseminate Info for MOOTW	All-Source Intel and Traffic, Personnel tracking	Non-Cooperative, Non-Lethal Target and Personnel recognition	Personnel (Facial) Recognition: Intel and Security	Terrain Visualization, Planning
7. Force Sustainment and Product Assurance			Non-Destructive Testing Image Analysis	Robotic Handling of Complex Components

3.4 General Model of Data Fusion

A general model of the data fusion process can be used to define the functional elements and the stages of the fusion process. We use the Joint Directors of Laboratories (JDL) general model[3] to compare target data fusion with multisensor ATR data fusion in which imagery data is fused (Figure 3-2). The JDL model distinguishes three processing levels: Level 1 processing performs the sensor-to-sensor data registration, correlation-association, and state/identity estimation, Level 2 performs situation assessment based on all data, and Level 3 assesses the threat content of the data. (A Level 4 is not shown, which includes management of the sensors and the internal fusion processes to optimize the process. Objective functions for optimization include: sensor emissions, target update rates, estimation accuracies, computation load utilization, etc.). The following paragraphs describe data fusion in the context of three of the four categories of data fusion.

Target Data Fusion—The generic JDL data fusion model (top sequence in Figure 3-2) illustrates the target data fusion process sequence in which multiple sensors (the collection assets) report the detection (or pre-detection raw measurements) of targets with associated state measurement data. The stages of processing include:

- **Preliminary Filtering**. Performed to remove noise and apply sensor-specific corrections (e.g., bias, gain and non-linearity corrections) to the data.

- **Alignment**. All measurements are placed in a common temporal and spatial reference frame by: (a) applying dynamic target models to extrapolate all state

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3. Franklin E. White, Jr., "Data Fusion Subpanel Report," in *Proc. Fifth Joint Service Data Fusion Symp.*, October 1991, Vol. I, pages 335-361.

measurements to a common sample interval, and (b) applying spatial transformations to bring all measurements into a common coordinate system.

- **Association**. New measurements are correlated with predicted states of all known targets to determine if each measurement can be assigned to update an existing track, used to start a new track, or eliminated as a false alarm measurement.

- **Tracking**. Sequences of data for any target are used to develop a dynamic target model which is used to predict the future location of targets (at time t+1) for association with new sensor observations and for correction of motion distortions.

- **Identification**. All of the associated data for a given target are used to perform automatic target recognition and to provide an assignment of the target to one or more of several target classes.

- **Levels 2 and 3 Processing**. The entire scene context is considered (terrain, target mix and spatial arrangement) to derive an assessment of the "meaning" of the scene in terms of threats, opportunities for engagement and probably intent of the targets present.

Image Data Fusion for Multisensor ATR—When image data must be fused to create a composite image for automatic target recognition, similar stages are performed, but the processes are different. Consider the process flow in which two dynamic imaging (video) sensors and a non-imaging (RF direction finding) sensor are fused to recognize a tactical target (lower sequence in Figure 3-2):
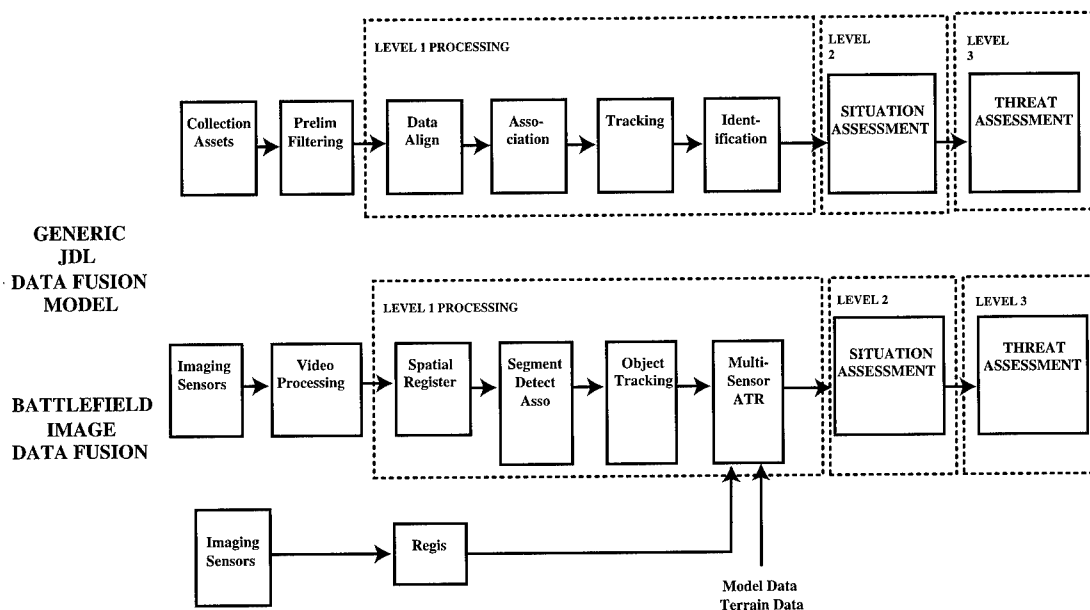
Figure 3-2. Data Fusion Functional Model is Shown for Target Data Fusion and Multisensor ATR Data Fusion Applications

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- **Video Processing**. Frequency domain filters limit noise bandwidth and remove narrow-band noise content.

- **Alignment**. The alignment of video data involves the application of spatial transformations to warp the image data to a common coordinate system (e.g., projection to an earth reference model or three-dimensional space). The non-imaging data are spatially referenced, not to a point in the image, but to a region with a specified uncertainty, from which the detected emission occurred.

- **Association**. First, target candidates are detected and data regions encompassing the candidates are segmented. Then, the current target candidates (at time t) are associated with previously detected objects (at time t-1) by scoring the likelihood of each hypothesis pairing. Based upon the likelihood of each pairing, assignments (of new measurements to existing targets) are made, or multiple assignment hypotheses are created and maintained for latter updating or deleting when reinforcing or contradicting data are found in subsequent images.

- **Tracking**. The objects are tracked in video by modeling the dynamics of target motion to predict the future location of targets (at time t+1) for association with new sensor observations and for correction of motion distortions.

- **Multisensor ATR Identification**. The segmented target data from multiple sensors are combined (at any one of several levels) to provide an assignment of the target to one or more of several target classes.

- **Levels 2 and 3 Processing**. The entire scene context is considered (terrain, target mix and spatial arrangement) to derive an assessment of the "meaning" of the scene in terms of threats, opportunities for engagement and probable intent of the targets present.

Spatial Data Fusion—Perhaps the most complex form of data fusion for *New World Vistas* applications is spatial data fusion to create a spatial model of a region of the earth, with spatial associations to all available intelligence data in the region. This process requires the combination of diverse sets of imagery [spatially referenced non-image data sets, two-dimensional (2-D) images and three-dimensional spatial data sets] into a composite spatial data information system. The most active area of R&D in this category of fusion problems is the development of geographic information systems (GIS) by combining earth imagery, maps, demographic and infrastructure or facilities mapping data (geospatial data), and textual intelligence reports (spatially referenced) into a common database.

In the *New World Vistas*, the Air Force must develop such spatial databases for intelligence preparation of the battlefield (IPB), mission rehearsal and use as the base map for target data fusion. (The Terrain Feature Generator component of the Advanced Research Projects Agency [ARPA] War Breaker project is one example of a major spatial database and fusion system developed to automate the functions of IPB and geospatial database creation from diverse sensor sources and maps.)

Figure 3-3 illustrates the basic functional flow of such a system, partitioning the Level 1 (Spatial Data Integration) functions that perform database generation from the Level 2 (Scene Assessment) function. The functional stages parallel the functions in the earlier applications.

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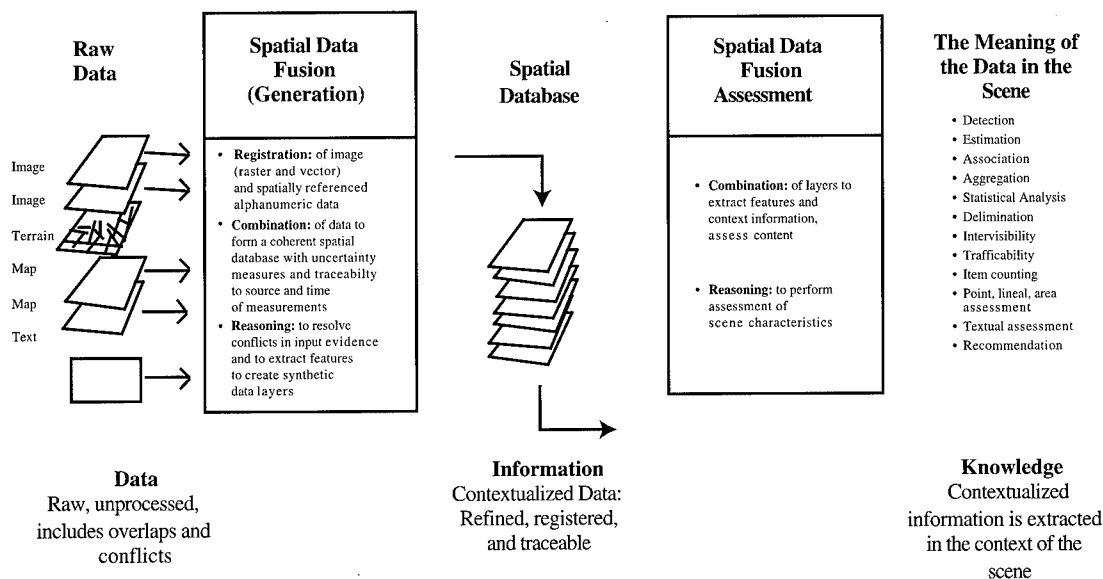
Figure 3-3. Spatial Data Fusion Process Generates and Maintains a Geospatial Database

- **Raw Data Preprocessing.** Data are accepted in a wide variety of physical and logical formats, all requiring conversion to acceptable raster or vector data formats. Maps are scanned, text messages are natural language processed, key words and spatial references are extracted, and raster (image) and vector (graphic) data are formatted. All data are augmented with metadata (data about the data sets) descriptors.

- **Registration (Alignment).** Incoming data of varying accuracies and resolutions are spatially registered and linked to a common spatial and temporal reference.

- **Association and Combination.** Higher-level spatial reasoning is required to resolve conflicting data and to create derivative layers of extracted features. Data layers are combined (mosaicking, creation of composite layers, extraction of features to create feature layers, etc.) to produce registered, refined, and traceable spatial data.

- **Reasoning (for Tracking Changes).** Changes in the data (e.g., road modifications, buildings, water levels, etc.) are identified in the data sets collected over time and are recorded. Configuration management is maintained on time tracked data.

- **Reasoning (for Identification of Features).** Features in the data are extracted and identified using the multiple layers of sensed data on any particular object. This process may require statistical pattern recognition over a single pixel or region (as in multispectral analysis), spatial analysis, or higher-level spatial reasoning.

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- **Scene Assessment.** The final step is scene assessment, which can be performed for a variety of application functions (e.g., further feature extraction, target detection, quantitative assessment, creation of vector layers, etc.) by a variety of user disciplines. This stage extracts information in the context of the scene and is generally query driven.

All of the data fusion models have a common set of processing problems which give rise to a taxonomy of design issues and system alternatives that are summarized in the next section.

3.4.1 Processing Taxonomy

Because of the wide range of applications for data fusion, the choice of system structural and functional processing architectures varies widely. The principal performance requirement parameters and operational considerations that impose constraints on data fusion system designers are summarized below:

- **Sensing Phenomenology.** The physical phenomena that are sensed, the discriminating characteristics of target classes, and interference phenomena (natural clutter, camouflage, concealment and deception) set ultimate limits on the achievable performance of the data fusion process.

- **Sensor Dimensionality.** The number of independent measured parameters (often referred to as observables) define the dimensionality of the total multiple sensor suite. The overall sensor load on the fusion process is quantified by the product of dynamic range (bits/sample) and sample rate (samples/second) for each dimension, summed over all contributing sensors.

- **Detection Performance.** The composite fusion detection performance is defined by the $P_{detection}$-to-$P_{false\ alarm}$ operating characteristic function (for single-sensor systems this is the well-known receiver operating characteristic). This composite performance requirement influences the choice of sensor pre-processing, uncertainty representation and inference approaches selected.

- **Information Accuracy.** The required accuracies for combined measurement estimates of state (three-dimensional location, velocities, etc.) and of identification parameters dictate the performance of individual sensors and the methods for representing and combining measurement uncertainty.

- **Information Currency and Latency.** Search rates, target revisit rates and processing speed are dictated by the requirements for currency (update rate) and latency (delay between sensor visits and delivered decisions) of fused information.

- **Security.** Requirements for multiple level security influence the combination processes and the methods chosen to assign security levels to data products that derived from multiple levels of secure data.

The taxonomy of processing alternatives that are influenced by these and other parameters are enumerated in Table 3-2. The taxonomy is based on five cardinal design trades that must be considered in any system design.

Table 3-2. Taxonomy of Fundamental Data Fusion Processing Alternatives

Processes	System and Processing Design Issue	Alternative Approaches
Representation and Management of Sensor Data Uncertainty	Level 1 - Select the most effective means to measure, represent and combine values of sensor uncertainty across all sources of data.	• Certain data (Boolean logic) • Uncertainty or confidence intervals • Probabilities (Bayesian inferencing) • Multi-Valued probabilities (Dempster-Shafer evidential reasoning) • Fuzzy sets (Fuzzy logic) • Random Sets (Combinatorial Algebras) • Multiple Hypothesis Maintenance
Representation of Knowledge	Level 2 - Represent and store information in a manner that permits efficient access, linkage and retrieval.	• Rules or Frames • Semantic Networks • Neural Networks • Graphical Relationships (space, time, spectrum) • Vector/Raster Spatial Data

Inference, Reasoning and Evaluation	Levels 2 and 3 - Partition (associate) and combine raw data to optimize the estimates of parameters about the source of data, and infer higher-level information about the source and its context.	• Induction
		• Deduction
		• Exhaustive or incomplete search
		• Default Inference
		  - Boolean
		  - Bayesian
		  - Evidential Reasoning
		  - Fuzzy

Processing Control	Level 4 - Control the sensing and processing functions in accordance with a defined objective function.	• Control Theory • Monotonic Reasoning • Non-monotonic Reasoning • Opportunistic Reasoning
Architecture	Interconnect sensors and sources in accordance with network bandwidth, security, distribution and processing constraints	• Centralized fusion processing at a common node in a network • Distributed fusion processing throughout a heterogeneous network

First, is the selection of a means to represent the uncertainty in sensed data. If the signal strength in individual sensors is high, each sensor may independently perform detection decisions and measure target features for combination. In this case, detection data is reported as certain and a simple Boolean rule (AND, OR) is all that is needed for detection fusion. If, on the other hand, sensor measurements are weak, raw signals with uncertainty measures may be used to perform composite detection decisions (and classification decisions). Numerous alternatives (listed in the table) exist to represent signal uncertainty and to combine uncertain data to express composite uncertainty.

Second, are the alternative methods to represent *a priori* knowledge (target signatures, relationships between signatures and entities, behaviors of entities, etc.) and knowledge accumulated by the fusion process.

The third design alternative is closely related to the chosen knowledge representation scheme: the means to evaluate and infer new knowledge based on *a priori* knowledge and composite information compiled from sensor measurements.

The fourth design alternative is the selection of a control structure to manage the sensing process (e.g,. sensor tasking, sensor mode control and emission control) and the fusion process. The management of sensors and the associated reasoning process can be closely coupled to adapt to a time-varying target load and is heavily influenced by each unique application environment.

The fifth alternative is the overall system architecture, which may employ centralized or distributed data fusion processes, depending upon factors such as sensor-processor distances, available network bandwidth, security, distribution (display) and processing constraints.

3.5 Challenges and Opportunities

The same "grand challenges" that face the general sensor area (noted in Section 3, "The Sensor Correlation and Fusion Process") apply to the fusion process because fusion is simply the process that allows a suite of sensors to be viewed as a single unit. These include: the ability to accept higher data rates and volumes, improved multiple sensor performance and improved multiple sensor operation. In addition to these, several additional challenges can be added:

- **Improved Integrated Sensors.** *New World Vistas* sensors will be designed from the ground up as elements of a multisensor suite, rather than as independent sensors with outputs that can be input to fusion. Integrated apertures, coordinated operating modes, synchronous sampling and common measurement reporting formats must be developed for these sensor suites to optimize the suite performance—both in management and collection efficiency.

- **More Robust Fusion Processes.** Fusion processes must be capable of accepting wider ranges of sensor data types (true "all-source" processes), accommodating natural language extracted text reports, precision-to-uncertain sensor measurements, historical data, and spatial information (maps, charts, images).

- **Improved Learning Abilities**. Fusion processes must develop adaptive and learning properties, using the operating process to add to the knowledge base

while exhibiting a sensitivity to "unexpected" or "too good to be true" situations that may indicate countermeasures or deception activities.

- **Enhanced Immunity to Information Warfare Threats.** Because the data fusion process is the node toward which all sensor data flows and information resides, it is the highest value target for information warfare attacks. System architectures must be designed to defend against: (a) active attacks (transmission or malicious code attacks), (b) deception, (c) disruption, or (e) exploitation.

- **More Robust Spatial Data Structures.** Efficient, linked data structures are required to handle the wide variety of vector, raster, and non-spatial data sources needed to perform global and regional spatial data fusion. Hundreds of point, lineal, and aerial features must be accommodated. Data volumes for global and even regional spatial databases will be measured in millions of terabits, and short access times are demanded for even broad searches.

- **Improved Spatial Reasoning Processes.** The ability to reason in the context of dynamically changing spatial data is required to assess the "meaning" of large volumes of spatial surveillance data. The reasoning process must perform the following kinds of operations to make assessments about the data: spatial measurements (geometric, topological, proximity, statistics, etc.), spatial modeling, spatial combination and inference operations in the presence of measurement uncertainty, spatial aggregation of related entities, and multivariate spatial queries.

4.0 Operational Tasks and Their Related Sensor Needs

4.1 Introduction

The Air Force faces critical roles in modern warfare, but the transition of thinking from the NATO versus Warsaw Pact Nation conflict to the regional conflict anywhere in the world presents yet a greater responsibility within the Global Reach—Global Power nature of the Service. The levels of conflict, with a near-continuous spectrum from peacetime to war, present challenges to sensor developers that are technically global.

The information needs of the various levels of command vary greatly for the major conflict and the buildup to that stage. Translated to sensor terms, the information need is for a continual, near-real-time, near perfect picture of the battlefield. This need is all-pervasive and spans the situation assessment, master attack planning, air tasking order preparation, mission planning, mission execution, battle damage assessment, and mission re-tasking. Figure 4-1 depicts the range of functions.

- **Peacekeeping**
  - Treaty Verification/Violation Detection
  - Diplomatic Leverage

- **War on Drugs**
  - Land & Sea Surveillance
  - Land Vehicles, Boats, Low/Slow Aircraft
  - Downlink to Enforcement Agencies

- **Surveillance**
  - World-wide Deployment
  - Precise Detection & Location
  - Individual Targets Presented in Overall Context

- **Situation Assessment**
  - Early Indication & Warning
  - Discern Intentions
  - Flag Mobilization/ Deployment
  - See and Understand the Situation
  - Diplomatic Leverage

- **Warfighting**
  - Low/Medium/High Intensity Conflicts
  - Contingency Operations
  - Precision Target Detection, Acquisition, Location
  - Surprise Attack Negated
  - Battle Management
  - Dramatic Shift in Loss Exchange

Stabilizing Influence

Peace

Power Projection/ Crisis Management

Decisive Influence

Conflict

Figure 4-1. Range of Military Operations

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A wide range of sensors is needed, though improved performance in cluttered and urban environments represents a more important capability enhancement than new sensor phenomenologies. Cost is of great importance in the current environment, not only the cost of the sensor itself but the cost of employing and maintaining the sensor system, whether it be on the ground, in an aircraft, or in space.

The targets of the future will be better hidden in the background in which they operate (stealthy), smaller, faster, and operating in all weather. Our sensors must be effective in such an environment, must be capable of identifying the target, and must be reliable. Table 4-1 matches the key missions and the associated general challenges.

Table 4-1. Mission to Challenge Mapping

Mission	Challenges
Counterair	Low Observable Aircraft and Cruise Missiles Long Ranges
Interdiction	Long Ranges Denied Territory Underground Targets
Close Air Support	Target Friend or Foe Large Target Densities
Surveillance and Reconnaissance	Wide Areas Denied territory Underground Facilities Low-Observable Ground Targets Perishability/Latency Dissemination
Special Operations	Denied territory Perishability/Latency Maintaining Survival/Covertness

Sensors will operate in the various classes of Air Force aircraft in use today (fighters, bombers, reconnaissance, transports) and the unmanned air vehicles (UAVs) of the future (reconnaissance and, perhaps, attack platforms). The UAVs will pose particular design challenges due to their constrained cost, size and weight, and perhaps the need for ATR to make up for limitations on data transfer rates. On the other hand, UAVs will provide unique capabilities of self-deployment world-wide, and very long on-station times.

Not every problem is solved by new sensors. We (the military in general) certainly have not learned to effectively extract information from the sensors, or combinations of sensors, we have now. Multisensor systems offer a tremendous potential, but only if we learn to effectively select the sensor combinations for the information they might provide, and properly combine data to derive useful information from these selected sensors. ATR techniques can include accessing or requesting additional data for the target identification decision and drawing on supplementary information sources.

For the purposes of identifying appropriate sensor concepts and the related enabling technologies, a set of representative operational tasks associated with the Air Force missions are

selected. The operational tasks are not all-inclusive but suffice to develop a context that spans the range of Air Force sensor functions. The selected representative operational tasks are:

- Acquire, maintain, and disseminate a full, near-real-time situation awareness picture of the battlefield.
- Maintain continuous world-wide surveillance of NBC weapon manufacture, storage, and transfer.
- Locate, observe, and target assets and activities in hardened/underground facilities.
- Acquire, locate, track, and identify ground targets to deliver munitions with high accuracy.
- Detect, track, intercept, and destroy theater ballistic missiles and cruise missiles.
- Acquire, maintain, and disseminate information to plan and execute special operations and military operations other than war (SO/MOOTW).
- Acquire information for force sustainment.

The use of these operational tasks as a framework for investigating sensor technologies does not suggest that the list is exhaustive. Rather, we have chosen these operational tasks to identify key sensor tasks which then define a range of specific sensor needs and approaches. Moreover, we recognize that there is overlap in the listed operational tasks. This overlap is to be expected, and the ensuing discussion will attempt to address the sensor concepts and technologies so as to serve all appropriate sensor tasks. Table 4-2 relates the operational tasks to the Air Force missions.

Table 4-2. Representative Tasks to Missions

Representative Operational Task	Air Force Mission
Maintain Situational Awareness	Counterair Interdiction Surveillance and Reconnaissance Special Operations
Find Weapons of Mass Destruction (Nuclear, Biological, Chemical)	Interdiction Surveillance and Reconnaissance Special Operations
Surveillance of Underground Facilities	Interdiction Surveillance and Reconnaissance Special Operations
Kill Air and Ground Targets	Interdiction Close Air Support Special Operations
Find Theater Ballistic Missiles and Cruise Missiles	Interdiction Surveillance and Reconnaissance Special Operations
Conduct Special Operations and Military Operations Other Than War	Interdiction Surveillance and Reconnaissance Special Operations
Gather Information for Force Sustainment	All

The following discussion of the selected operational tasks is a top-down approach to identifying the sensor concepts and technology needs for the Air Force of the year 2025. It identifies the functions associated with each operational task, establishes the critical challenges for the future, then formulates sensor concepts and technology solutions to achieve the needed capabilities.

4.2 Battlefield Situational Awareness

Operational Task: Acquire, maintain, and disseminate a full, near-real time situation awareness picture of the battlefield.

4.2.1 Description of Operational Task

Tasks that support the acquisition, maintenance, and dissemination of a full, near-real time situation awareness picture of the battlefield include:

- Collect and fuse data from all available civil, diplomatic, and military sources including surveillance, reconnaissance, intelligence and operational information on order of battle and own force status, as well as history, economics, culture, geography, geology, trafficability, weather, hydrology, and so forth.

- Maintain multiple copies of the database, each containing appropriate information relevant to the scope of the intended user community, for example, from the President to the Private.

- Extract data on short notice from the national level system that is relevant to an anticipated potential crisis area and route it to a suitably equipped crisis management center or operational user.

- Index, organize, cross-reference, and distribute data for storage and use at multiple locations (from a national crisis center to a theater command center, to a squadron command post, to an on-aircraft data terminal).

- Perform dynamic distributed "truth maintenance" functions across databases at all levels.

- Detect and reject incorrect data inserted by enemy information warfare.

- Flag for further analysis specific items of interest and changes that exceed user specified bounds or historic norms.

- Present appropriate "views" of the information for users, highlighting changes and specific items of interest and enabling the user to rapidly gain an up-to-date mental model of the situation.

4.2.2 Sensor Challenges

The United States has enjoyed a long period of military and commercial sensor dominance that is now eroding as other major powers improve their capability and supply smaller countries with very capable information-gathering systems. There is a need to develop technologies that maintain or regain the advantage over our potential adversaries.

Of particular importance are the challenges associated with detecting and locating:

- Targets in hides, such as berms, tunnels, underpasses, caves, and canyons.

- Targets concealed in foliage and camouflage.

- Targets with highly reduced observables (radar cross section, infrared signature, acoustic noise, electromagnetic radiation, and visual image).

- Targets for which there are non-military objects that have a strong resemblance such that determining military targets is very difficult.

4.2.3 Applicable Sensor Concepts

There is a critical need to structure a global surveillance architecture that capitalizes on the attributes of satellites (GEO, LEO); unmanned air vehicles (high, medium and low altitude and endurance); manned aircraft; and ground/surface sensors in an affordable, yet capable way. The architecture would include the following concepts:

- Space based sensors will provide wide area coverage with active monostatic and bi-static radar, laser sampling, and passive hyper-spectral optical instruments.

- Unattended sensors will report measurements of interest spontaneously or when asked.

- UGS and minidrone/robotic (bumblebee) sensors will be implanted in advance or in response to crisis and provide detection, classification, ionization, hypothesis formation, and communications through appropriate readout/relay platforms.

- All useful information will flow to the master distributed database and in parallel to all interested users. Fusion of multisensor data will refine and clarify fuzzy hypotheses initially derived from single sensor data.

- National and theater databases provide storage, archiving and retrieval services. Generation of database queries, with fusion of data from multiple independent sources and partially fused intermediate results will take place at all levels that have access to outside data and the necessary processing assets.

4.2.4 Enabling Technologies

Many of the technologies that enable this vision of global situation awareness are communications and information technologies. Among the most challenging are:

- Fast, large, ultra reliable secondary and tertiary mass storage devices with built-in processing for indexing, cross-referencing, and retrieval.

- Fuzzy hypothesis formation and intelligent agents for distributed truth maintenance.

- Low cost, moderate power, tunable, coherent lasers.

- For space based radars: high efficiency, light weight solar cells and power conditioning; high efficiency RF conversion, light weight, high gain antennae; and low power, ultra-reliable spaceborne processors.

- Analog-to-digital converters with both higher sample rates and higher linear dynamic ranges.

- Database fusion, correlation, storage, and query techniques to quickly access data or task sensors to collect further data.

4.3 Surveillance of Weapons of Mass Destruction

Operational Task: Maintain continuous worldwide surveillance of NBC weapons manufacture, storage and transfer.

4.3.1 Description of Operational Task

The objective of this operational task is to maintain continuous world-wide surveillance of sites that manufacture, store or transport NBC weapons. This includes the requirement to:

- Reliably detect and characterize each manufacturing site, including having knowledge of the volume and type of NBC material being produced; understanding the relationship of the NBC material and its "cover" production material; and completely describing the factory production process.

- For storage sites, determine the location of the sites, the amount and type of material or weapons stored, and the relationship to other "cover storage " materials. Any movement in or out of the site, and even relocation within the site should be monitored, with particular attention given to those observables that might indicate intention.

- The transport information includes a description of the location, time, and means of transport of the material to other sites for storage, or to the weapon delivery system (such as a ballistic missile launcher).

- An additional information need occurs after attack of a site. In this case it is desired to know if the material in question was destroyed and, if not, where it is being dispersed.

4.3.2 Sensor Challenges

Since many of the NBC sites are intentionally hidden, the sensor challenges are driven by a lack of direct observables. Direct signatures of production process byproducts such as gas effluents, thermal energy imbalance, nuclear events, and so forth are rarely available or are ambiguous, are available too late for desired counter action, or are very weak so that they are easily confused or masked by other natural events. Weak signatures also make detection via remote sensing techniques difficult for all but very small areas because of the long integration times needed to achieve reliable signal measurement.

4.3.3 Applicable Sensor Technologies/Concepts

A world-wide "map" database should be developed with a risk (likelihood that NBC materials are at the site) assessment for each candidate site. This risk index includes a confidence level and is continuously updated as new information is made available.

Several new sensor information sources can contribute to the overall NBC information fusion and collection tasking capability. They are described below:

- **Economic, Supply and Development Information.** This information deals with the equipments and raw materials purchased by companies/countries (perhaps obtained from world-wide delivery companies like Federal Express, etc.), the plans for construction of new facilities, the support infrastructure for new sites (energy, water, waste removal), and the energy balance and product (material) output of a site (including waste byproducts).

- **Ground and Near-Ground Based Microsensors.** This class of sensors are micro-machines and point measurement/sampling sensors that can support a wide variety of measurement phenomenology, including acoustics, seismics, thermal radiometry and imaging, spectroscopy, tilt, magnetics and vibration. The sensors can be delivered by air or through covert implantation via agents or special operations. Point sampling can also be accomplished by airborne sampling via miniature UAVs or ground-based crawling machines (from insect- to rat-sized).

- **Enhanced Active/Passive EO/IR (Spectral) Sensing.** This sensor concept utilizes advanced focal planes and tunable filters to support passive hyper-spectral remote sensing. Tunable lasers are used for narrow-band active spectroscopic sensing of gas and materials. Technology growth will support increased sensitivity, larger search rates and reduced false alarms. The sensors can also be miniaturized for man portable units to be carried by Special Operations personnel.

- **Supply Chain Tagging.** This sensor concept is related to the above in that special materials/devices are used to mark materials or vehicles with unique signature generation devices or coatings. Many tagging materials can provide unique spectroscopic signatures that can be measured hyper-spectrally by systems as discussed above. The techniques allow sensing and tracking of supply materials and final products as they relate to specific production facilities.

- **Stimulated Response.** Because the candidate site are well hidden and the observables are well controlled, alternative means are needed to confirm the site purpose. One approach is a "closed loop" measurement scheme whereby specific misinformation about the site is publicly released to cause the adversary to take action to further protect/deny/cover its existence. For a specific site, the strategy is to stimulate a new observable which is not consistent with the alleged factory purpose and thus would provide a cue of covert NBC activity.

4.3.4 Enabling Technologies

Many of the sites are intentionally hidden and masked where possible. Only indirect indicators were identified to characterize each candidate site. The detection of candidate sites

without collateral information is an open (unsolved) problem. The observables identified are only partial indicators of site purpose. The optical remote spectroscopy and ground sensor, coupled with tagging devices, are the only viable means to gather the partial indicators of site activity. Fusion of site information and process models are the only methods identified to accurately characterize a site.

Specific enabling technologies include:

- Small, tunable lasers support active spectroscopy to detect and analyze effluents from the sites.

- Low cost focal plane arrays, tunable filters to support passive spectroscopy.

- Femtosecond lasers and laser radar systems to provide molecular identification.

- Micro-electromechanical systems required for covert point unattended ground sensors.

- Tagging materials that can be covertly embedded in materials to support material tracking.

- Adaptive tasking algorithms to support information gathering strategies based upon confidence levels.

- Information fusion stations for supporting multiple information source fusion for NBC sites data.

4.4 Surveillance of Underground Facilities

Operational Task: Locate, observe, and target assets and activities in hardened/underground facilities.

4.4.1 Description of Operational Task

Countries (developed and developing) are, on an increasing basis, constructing and relocating their critical military complexes and facilities for production of weapons of mass destruction (WMD) underground. The reasons are twofold: the facilities are more difficult to detect and monitor, and they are much more difficult to neutralize/incapacitate/destroy.

The functions of air power in reference to UGFs for which sensors would have an important role are:

- **Surveillance of Underground Facilities.** Collecting information about a UGF, its characteristics, and any associated activities to:

  - Verify that an underground facility is present in the area

  - Determine the geographic location of the facility

  - Determine the function of the facility

  - Determine the characteristics of the UGF

  - Determine and measure operating signatures and monitor activity at site

- **Mission Planning and Targeting**. Providing information about critical components, meteorology, and the positioning of aim-points; identify and locate equipment and LOCs critical to site operations.

- **Strike**. Support fusing and verifying a weapon's performance, including real-time battle damage assessment.

- **Post-Strike Battle Damage Assessment**. Providing data about the effectiveness of the strike, weapon performance, collateral effects, and repair activities, including:

  - Assess the damage caused by the strike and its environmental effects

  - Monitor the reconstruction and the activity levels of the facility

4.4.2 Challenging Sensor Needs

The challenges associated with underground facilities are related to the fact that these facilities are designed to be undetectable. Therefore, we must employ sensors that can "penetrate" earth to detect a void or man-made structure or employ indirect means of detection such as observing collateral activity, effluents, machinery vibration, and so forth.

The phenomenology determines how and which UGF features are observable with certain kinds of sensors. Table 4-3 is a representative example of features, their observables, and the associated parameters of observation.

4.4.3 Applicable Sensor Technologies/Concepts

Because mission requirements involve the detection and monitoring of almost all UGF features, potentially useful sensors include virtually all types: electromagnetic, photographic, seismic, acoustic, chemical, biological, and so forth. Table 4-4 lists some of the more promising kinds of sensors for detecting and monitoring UGF features.

4.4.4 Enabling Technologies

Since the UGF task is so encompassing and may require all forms of sensors in performing the associated functions, a wide variety of enabling technologies are also relevant. Some of the enabling technologies associated with the specific sensor concepts indicated above are summarized here:

- **Arrays of Seismic and HF EM Sensors With Tomographic Processing**. The key technology to be developed for this concept is the seismic and HF tomographic processing technique for dealing with both amplitude and phase over a band of frequencies of a decade.

- **LIDAR for Effluent Analysis and Vibration Detection**. Small, tunable, solid state laser sources suitable for UAV operation are needed.

- **Unattended Ground Sensor (Chem/Bio, Acoustic, Electromagnetic)**. The development of small, near-real time chem/bio sensors is the key technology challenge for this class of sensors.

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Table 4-3. Representative Features, Observables, and Parameters

Example Features	Physical Observables	Observable Parameters
Effluents Gaseous	Vegetation, Rock Varnish, Chem/Bio Agents	Spectral Absorption, Emissivity, Luminescence, Microwave Reflectivity, Chem/Bio
Liquid	Vegetation, Rock Varnish, Chem/Bio Agents	Spectral Absorption, Emissivity/Reflectivity, Luminescence, Microwave Reflectivity, Chem/Bio
Communications Signals Electromagnetic Emissions	Electromagnetic Radiation, Vegetation Effects	Microwave Emissivity, Spectral Reflectivity
Antenna Complex	Antennas, Heating, Electromagnetic Radiation	Spatial Arrangement, Temperature Differences, Microwave Reflectivity
Size and Layout	Cavity, Structural Members	Gravity Gradient, Magnetic Gradient, Telluric Properties
Construction Materials	Shielding, Materials	Magnetic Gradient, Resistivity
Transportation Roads & Rails	Roads & Rails	Spatial Arrangement, Thermal Properties, Spectral Reflectivity, Microwave Reflectivity
Runways & Helipads	Runways & Taxiways, Water Channels	Spatial Arrangement, Spectral Reflectivity, Thermal Properties, Microwave Reflectivity
Electrical Power	Power Lines, Transformers, Heat Production,	Spatial Arrangement, Thermal Differences, Microwave Reflectivity
Heat Exhaust	Heat Dissipation, Vegetation Effects, Snowmelt	Thermal Properties, Spectral Reflectivity, Microwave Reflectivity
Air Handling Components	Intake & Exhaust Ducts	Thermal Properties, Vibration
Operations Machinery	Surface and Air (Sound) Vibration, Electromagnetic Emissions	Vibration
Process (Raw) Materials	Materials, Storage Areas/Containers, Vegetation & Soil Effects	Spatial Arrangements, Spectral Absorption/Emissivity, Spectral Reflectivity, Luminescence
Location Far From Population Centers Near Military Facilities	Context Context	Spatial Arrangement Spatial Arrangement

- **HF/VHF Interferometric SAR.** This involves the development of narrow notch filters and processing techniques involving adaptive apodization to produce image point spread functions with low sidelobes to reject interference. Other enabling technologies related to this concept are ultra-wideband airborne antenna structures (approaching 100 percent bandwidth), high power, ultra-wideband components,

for example, switches, and analog-to-digital converters, to deal with the very large dynamic range of signals associated with this application. Coherent change processing allows the detection of very small (few mm) subsidences and subtle surface disturbances. The development of improved image registration algorithms is important to permit the application of this concept.

- **Weapon-Borne BDA Sensors**. These sensors will accomplish battle damage assessment (BDA). High "g" forces must be endured, and a method must be found to communicate the assessment to the delivery aircraft, or to our forces, to determine if re-strike is required.

Table 4-4. Sample Features Versus More Capable Sensors

Example Features	Sensor Type								
	VIS	M/H	US	TIR	SAR	GPR	LAS	GEO	NBC
Effluents Gaseous Liquid		X X	X X				X X		X X
Communications Electromagnetic Emissions Antenna Complex	X	X		X X	X			X	
Size & Layout						X		X	
Construction Materials						X			
Transportation Roads & Rails Airports & Helipads	X X	X X		X X	X X				
Electrical Power	X			X	X				
Heat Exhaust		X		X	X				
Air Handling Components				X	X		X	X	
Operations Machinery					X		X	X	
Process Raw Materials	X	X	X				X		
Location Far From Population Centers Near Military Facilities	X X								

X	Likely the better class (maybe more than one) of sensor for observing the feature based on phenomenology
VIS	Visible and near infrared sensors (photo/electro-optical)
M/HS	Multispectral/Hyper-spectral sensors
US	Ultraspectral sensors
TIR	Thermal infrared semsprs (single/multiple band)
SAR	Symthetic aperture radar sensors
GPR	Ground-penetrating radar sensors (maybe similar to SAR, but designed for sub-surface imaging)
LAS	Laser sensors including molecular absorption, scattering, vibrometry, luminescence
GEO	Geophysical sensors, includes seismic, acoustic, magnetic, gravimetric, EM sensors
NBC	Nuclear, biological or chemical sensors

4.5 Accurately Deliver Munitions

Operational Task: Acquire, locate, track, and identify ground targets to deliver munitions with high accuracy.

4.5.1 Description of Operational Task

Targets to be attacked include theater ballistic missile transporter-launchers, aircraft parked in revetments, enemy command posts, bridges, weapon storage sites, manufacturing plants, enemy tanks, personnel carriers, and troops. Mobile or relocatable targets require different weapons targeting strategies than fixed targets. The effective destruction of targets requires successive steps:

- Wide area search and localization of the target, or of a target rich area so as to cue the attack.

- Target acquisition to provide accurate identification and location of the target such that a weapon can be directed to the target aimpoint.

- Flyout and midcourse guidance of the weapon.

- Terminal guidance of the weapon/munition, either as a continuation of a precision midcourse guidance, or as a terminal seeker acquisition and guidance to the aimpoint.

- Observation of the munitions effects for the purpose of BDA as required to determine whether re-attack is necessary.

4.5.2 Sensor Challenges

Successful destruction of air and ground targets requires a number of sensor-related challenges:

- For an uncued air-to-ground (A/G) situation, search up to 15,000 square km per hour (a 750 km by 20 km area), with no more than one false weapon release. A targeting sensor may be cued by some other sensor, but in some cases it will not be cued. For those cases, we need a search capability.

- For the air-to-air (A/A) situation, sense all targets within an elevation of 60 degrees and an azimuth of 360 degrees.

- Weapon release should be available at maximum weapon range. This means target detection, recognition, ID, and identification friend, foe, or neutral (IFFN) has occurred. In addition, target priority has been determined and a firing solution has been achieved—all prior to reaching maximum weapon release range.

- Targets should be acquired in all weather conditions, day and night. Targets obscured by CCD or foliage, inside revetments or bunkers, or otherwise concealed must be located and classified.

- As the weapon approaches the target, the location of the weapon relative to the target must be determined more accurately and at a higher update rate until impact.

- Bomb damage assessment is essential to determine if a target has been killed, or must be attacked again.

4.5.3 Applicable Sensor Technologies/Concepts

Target attack capability depends on a mix of EO/IR and microwave systems for affordability, accuracy, weather resistance, and jam resistance. Some of the more important elements are:

- Multispectral EO/IR sensors for wide area A/G search.

- Determination of local weather/environment to establish selection or delivery of weapons.

- High bandwidth (high range resolution) microwave A/G sensors to reduce pixel size such that clutter within a pixel is within the limits that can be handled by later stages of the targeting process, but without the long dwell times associated with synthetic aperture derived angle resolution.

- Laser radar for target identification. Preferably, the same system does laser designation.

- Modulatable corner cubes on the target for covert handshake and IFFN determination.

- Covert radar approach to target identification handshake. This could employ a modulatable corner cube similar to the idea put forward for laser radar.

- Low cost three-dimensional laser sensors for use as seekers. With microwave radar or GPS coordinates as an initial targeting source, and then GPS/inertial to put the weapon in the basket, even a short range three-dimensional laser radar can do the final correction, especially if the weapon has a "high g" maneuver capability.

- SAR with 0.3 meter resolution and 10 meter target location accuracy for the weapon-carrying aircraft, and some method of locating the weapon to 10 m accuracy, so we can use command guidance to reduce weapon cost.

4.5.4 Enabling Technologies

The enabling technologies for the target attack operational task include:

- Affordable modular, integrated, multifunction EO/IR sensors.

- Modular, integrated, multifunction RF sensors.

- A very low cost, lightweight, three-dimensional laser radar for missile seeker use—with as much atmospheric penetration and smoke penetration capability as possible. A baseline would include a 32 by 32 high bandwidth imaging laser radar detector array at about 1.5 μm, with an alternate wavelength at 3.5 μm for smoke penetration. This is possible using an optical parametric oscillator, and a 1.06 μm laser as the drive laser.

- A low cost, but very accurate, inertial measurement unit (IMU) to allow the weapon position to be known, even after GPS is jammed. The better the IMU, the more accurate the weapon is. If we have a final seeker guidance correction, such as with a three-dimensional laser seeker, a better GPS means less correction is required.

- 1 GHz bandwidth microwave radar (probably at X-band) for high range resolution SAR. Bandwidths of 2 or 3 GHz would provide for even greater range resolution.

- A multispectral passive imaging IR sensor for wide area target detection.

- A tunable laser radar for target detection and identification of partially obscured targets.

- ATR techniques for rapid target identification.

4.6 Find Theater Ballistic Missiles and Cruise Missiles

Operational Task: Detect, track, intercept, and destroy theater ballistic missiles and cruise missiles.

4.6.1 Description of Operational Task

The United States can expect to face a theater ballistic missile (TBM) and cruise missile (CM) threat in future conflicts. In addition to the political disruption like that caused by the Scuds in the Gulf War, we are likely to face more accurate TBM/CM systems that can pose a meaningful threat to military systems, including NBC warheads. Our options begin with preventing use by destroying the equipment on the ground before the missiles are launched. Sensors for this role are discussed in Section 4.5. The next option is to deter use by holding the launch sites at risk when they launch. To do this requires sensors to find the sites and to guide munitions to attack them.

We will also attempt to destroy any missiles that are in flight. This can be done either in the terminal phase or in the boost phase for theater ballistic missiles. In the first of these cases, because the re-entry vehicle (RV) is on a ballistic trajectory, the debris (which may include chemical and biological warfare agents) will land in the defender's territory. Boost phase intercept, on the other hand, will deposit the debris in the shooter's country. In addition, if the missile has multiple warheads, boost phase intercept will kill them before they can be separately deployed (warhead fractionation). For terminal defenses, the missiles are ground based, and the seekers and FC systems will be developed and fielded by the Army and Navy. They will need sensors for warning and cueing, and these are likely to be airborne or spaceborne sensors fielded by the Air Force. Boost phase intercept will require airborne FC sensors to meet the stressing engagement timeline.

Destruction of cruise missiles in flight is difficult due to the small size (in both physical and signature senses) and the typically low altitude ingress. If the enemy is using cruise missiles to saturate our air defenses, multiple simultaneous engagements will be required. Cruise missiles may employ electronic countermeasures (ECM) such as terrain bounce jamming or towed decoys.

4.6.2 Sensor Challenges

To detect and locate a missile launcher before it launches a weapon is extremely difficult. Large areas, many hide locations, and frequent movement offer significant and, as yet, unresolved challenges to the Air Force.

After a launch, the launcher can be localized for counter-battery attacks to some extent by tracking back on the missile trajectory. If there is a weapon that can attack the launcher before it is able to move, it can be engaged; this requires either a very fast weapon, a weapon platform that can maintain fast PGMs close to the launch site, or both.

The major challenges in cueing for terminal defenses lie in the rapid acquisition and dissemination of information; the basic sensor requirements can be met with current systems, or evolutionary improvements, although improvements in IR sensors may ease this challenge by allowing small cheap satellites that can be under the control of theater commanders (see 5.2.7).

For boost phase intercept, the hardest challenges are in the weapons. The nature of the sensor challenges depends on whether directed energy (laser) or a missile is used as the weapon. For the case of the laser, the biggest challenges are aiming the laser to a fraction of its 0.5 micro-radian beam, and compensating for atmospheric distortions over a long path. In addition, if the laser cannot be maintained in a ready state, the launches must be detected before cloud break.

To attack cruise missiles in flight, we need novel seekers that can cope with the very small signatures. Techniques that can place the sensors close to the flight path are important. For the possibility of saturation attacks, high firepower surface-to-air missiles and fighters capable of multiple long range engagements are needed, with accompanying surveillance and missile guidance sensors.

4.6.3 Applicable Sensor Technologies/Concepts

For missile detection above the cloud deck, we can use space-based infrared sensors, either in GEO or, with LIGHTSATS, in LEO. The principal challenges here are to process and distribute the information. It will also be challenging to make the low earth orbit satellite system affordable in the required quantities.

An EO/IR sensor system on an aircraft could be used to precisely and rapidly locate missiles above the cloud deck. Such a system could be placed on surveillance assets normally flying in-theater such as AWACS or Joint STARS, on HAE UAVs, or on such aircraft sensor systems as Cobra Ball.

To detect a launch below the cloud deck requires either a network of ground based IR sensors deployed around the potential launch areas or radars, which may be airborne or space-based. The radars would seem to be a better choice since they can perform other missions, such as air surveillance, at the same time they look for TBM launches. The choice between airborne or space based radars will depend on the technology and the nature of the other uses desired from the system. If the system must hand off to an optical system, it may be necessary to have the radar located near the optical system to deal with the effects of atmospheric refraction. It may also be necessary to switch from a low frequency search radar to a higher frequency tracker to get sufficient accuracy for handover to a fine optical tracker.

To direct a laser weapon to the required accuracy will require an optical FC system, like the one planned for ABL. This will probably be a passive IR sensor, although an active sensor with a sensitive detector (like an APD array) might also be possible. Sensors to allow atmospheric compensation have been developed, and the technical challenge posed by compensation for long propagation paths is being investigated. An interceptor missile would likely have midcourse guidance from the radar that found the launch with handoff to an IR homing seeker.

Tracking a launcher for the time it takes to bring a weapon to bear can be accomplished by several approaches. One is a spaced based radar that can provide continuous coverage. It could be cued by the launch detection system to an accuracy limited by the accuracy of trajectory tracking. It would probably need both SAR to find the launcher and MTI to track it, and it may need to penetrate foliage. Such a sensor could be placed aboard airborne platforms, including UAVs and Joint STARS. Another choice is a collection of sensors deployed in the launch area, which could be acoustic or optical, that can track the target and respond to interrogation by the attacking aircraft. Alternatively, the launch vehicle might be tagged in some way to allow an attack aircraft to follow its track, perhaps with some material on the tire that leaves a trail that can be detected.

The detection of cruise missiles in flight requires high power-aperture product radars on air or space platforms, as well as novel seekers proliferated on the ground to detect low flyers. The use of HF and VHF radars capitalizes on the fact that the size of the target is on the order of the wavelength of the radar, such that normal RCS reduction techniques are less effective. Proliferated ground sensors employing acoustic and infrared detection will be effective. Detection sensors must be closely coupled with the FC and kill systems because of the time sensitivity of the solution.

4.6.4 Enabling Technologies

Many of these sensor needs can be met by current technology or incremental improvements. Providing the constant surveillance and rapid communications required for boost phase intercept and counter battery missions will require improvements in the information technology employed. The technologies associated with the detection and neutralization of cruise missiles are further discussed in the 1993 AFSAB Summer Study, "Options for Theater Air Defense."

Wide area surveillance sensors coupled with techniques for area delimitation may help in the search for launchers.

To provide nearly continuous space-based radar coverage for counter battery operations will require several SAR sensor systems in low earth orbit (LEO).

Optical FC systems with passive or active IR sensors are important to this task, including development of the sensor, optics, and pointing subsystem for an airborne boost phase intercept laser.

Ground based unattended IR and acoustic sensors with processing and communications may be useful for missile track reporting and transporter-erector-launcher (TEL) tracking.

High power-aperture product high frequency (HF)/very high frequency (VHF) and ultra high frequency (UHF) radar components, such that these sensors can be carried aboard such

aircraft as AWACS and some HAE UAV, are promising approaches to detection of concealed targets.

4.7 Special Operations and Military Operations Other Than War

Operational Task: Acquire, maintain, and disseminate information to plan and execute SO/MOOTW.

4.7.1 Description of Operational Task

The special operations mission, more than any other military mission, must be carried out successfully the first time. As history has shown, the failure of such a mission, usually a one-of-a-kind mission carried out by small elements, becomes a national embarrassment and international news at a minimum. Thus the forces must be fully equipped, very well informed, completely trained, and thoroughly rehearsed. In an age of many rapidly evolving technologies on both sides, this is a significant challenge. As an example, the Special Operations forces typically had the night as their friend. That is, they could operate with relative impunity at night. Advances in night vision equipment and in radar have given our adversaries the capability to detect special operations at night and in poor weather, threatening the success of those operations and the lives of the special operations forces (SOF).

The SO/MOOTW mission area includes an ever-increasing series of roles in the modern world. The Air Force missions include:

- Successfully, survivably, and perhaps covertly infiltrate and exfiltrate personnel, equipment, and supplies in denied territory.

- Apply precise firepower in small areas to support military entry/exit, and combat or non-combat rescue.

- Support counter-terrorism operations.

- Provide counter-drug surveillance and intercept.

- Assist in humanitarian operations.

In fact, SO/MOOTW is the "now" war, "fought" every day in many locations around the world. In the future, SO/MOOTW will have an increasing role in the world, with particular emphasis on counter-terrorism and counter proliferation. One-of-a-kind missions will be the rule, rather than the exception.

4.7.2 Sensor Challenges

The sensors envisioned for the SO/MOOTW missions vary from small, covert unattended sensors up to airborne (on-board and off-board) sensors and even space-borne sensors with a wide range of capabilities. Concentrating on the SO/MOOTW unique sensors, the needs tend to be peculiar to a particular mission, rather than the broad applications associated with other Air Force elements. Table 4-5 depicts the key sensor challenges.

Table 4-5. SO/MOOTW Sensor Challenges

Capability	Challenge
Infiltrating and exfiltrating personnel, equipment and supplies	Maintaining covertness and/or survivability of relatively large aircraft
Detecting, locating and tracking humans in buildings	Penetrating walls, shields, rubble Low signature of humans
Locating and identifying electronic equipments	Low emissions levels Equipment in standby
Inspecting containers for contents	Penetrating containers Identifying contents
Tracking illegal cargo movement	Penetrating containers Wide search/track area Small signatures
Establish intent of humans	Small signatures
Determine and monitor underground activity	Earth/facility penetration
Locate and monitor weapons caches	Foliage penetration
Identification of objects	Sub-pixel resolution

4.7.3 Applicable Sensor Technologies/Concepts

Specific technologies that might aid the SO/MOOTW mission area include some that are unique, and many that are common with other mission areas. The SOF need many of these sensor technologies to conduct day-to-day operations now. Their missions, and the accompanying sensor requirements, will grow with time.

The general requirements include building penetration and foliage penetration radars, as well as radars and LADARs associated with target identification. These sensors must be packaged for use in transport-class aircraft, or for easy transport and air drop. In general, however, there is the need to develop small, lightweight sensors for easy and, perhaps, covert deployment and employment. Table 4-6 depicts the sensor technologies/concepts more specifically.

4.7.4 Enabling Technologies

The enabling technologies supportive of the Special Operations and Military Operations Other Than War operational tasks include miniaturized versions of many of the conventional technologies.

- Miniature focal plane arrays combined with acoustic/seismic/tilt transducers, and GPS in very small packages.

Table 4-6. SO/MOOTW Sensor Needs

Sensor Type	Sensor Concept
Building penetration radar	MTI range gated radar RF/Seismic Sensor with Tomographic Processing
Advanced sensors	Laser Radar Femtosecond Laser Radar Induced Fluorescence Tunable Laser Radar Differential Absorption Laser
Multispectral imaging	Multispectral infrared focal plane arrays
FOPEN radar	Low frequency, wideband synthetic aperture radar Gated laser radar
Building implantable sensors	Miniature spectrometers inserted with food supply to detect chemicals and effluents Miniature seismic, audio, and radio frequency sensors inserted covertly
Tags and detectors	Optical corner cubes with controllable/variable phase shift Electronic tags inserted in food supply Electronic tags implanted in friendly personnel Sensor/tags inserted in equipment manufacturing process
Personal (anxiety, stress, etc.) sensors to detect adversary's intentions	Temperature, heart rhythm, eye movement sensors implanted with food supply Miniature spectrometers inserted with food supply to detect chemicals and effluents
Effluent detection	Differential absorption laser Femtosecond Laser Radar Miniature chemical sensors

- New technologies for UGS, including new transducer fabrication and integration methods such as the MEMS technology.

- Chemistry lab on a chip technology to produce a micro-miniature effluent and agent detector-reporter.

- Tags made even smaller than current designs (micro-tags) could map water, sewer, and air flows which, in turn, could help map areas and buildings, and even help locate humans and equipments.

- Multispectral apertures (e.g., infrared (IR) with millimeter wave (MMW) and multicolor IR) are required, as are low cost, moderate power, tunable, coherent lasers, and analog-to-digital converters with both higher sample rates and higher linear dynamic ranges.

- Micro-miniature radio frequency sensors, perhaps square-law detectors on a chip to detect even LPI radiations using unattended sensors placed close to LOCs.

4.8 Information for Force Sustainment

Operational Task: Acquire information for force sustainment.

4.8.1 Description of Operational Task

A major application of sensors in Air Force operations concerns maintenance, system inspection, quality assurance, and other aspects of providing a combat-ready force. The overall vision is of a force structure in which weapon systems have high intrinsic reliability through design for long failure-free lifetimes and are essentially self-supporting under operational conditions with little or no external infrastructure required beyond replenishment of consumables. For example, diagnostics built into a combat aircraft returning from a sortie should be able to determine and report the status of the aircraft and its systems in enough detail to enable a decision on whether to send the aircraft to an integrated combat turn or to a repair point. Important elements of this task include:

- Fast, accurate, and precise diagnosis of failures and damage.

- High throughput, thorough, and affordable inspection of aircraft and other equipment for wear, corrosion, damage, or other problems.

- Maximum system autonomy, resulting in minimum requirements for specialized equipment and technicians.

- Rapid, high fidelity inspection of procured or fabricated parts and materials to ensure compliance with specifications.

4.8.2 Sensor Challenges

Better sensing capabilities are important across the spectrum of system support (see also 1994 Air Force Scientific Advisory Board Summer Study, "Life Extension and Mission Enhancement for Air Force Aircraft"). Some key sensor challenges include:

- Embedded diagnostics with the ability to accurately determine the status of hidden aircraft structures, hydraulic/pneumatic systems, electrical systems, engines, and avionics.

- Continuous and automatic maintenance sensor calibration, lubricant, and filter monitoring.

- Current nondestructive inspection/evaluation/testing (NDI/NDE/NDT) techniques for corrosion, cracks, leaks, and other problems are manpower intensive and generally require cumbersome equipment and long inspection times, restricting much of this surveillance to periodic depot visits.

- Determining the condition of parts, assemblies, and materials in storage (dormant reliability) without installing those items in weapon systems.

4.8.3 Applicable Sensor Technologies/Concepts

In general, the key to success in meeting these challenges is the deployment of small, cheap, intelligent sensing devices for a wide range of mechanical and electrical properties, backed up by data processing to extract the required information. Specific concepts include:

- **Advanced Built-In Test/Fault Isolation Test (BIT/FIT).** BIT/FIT can employ information from a wide variety of sensors, especially using machine reasoning in onboard processors to interpret the indications. Techniques and standards (e.g., IEEE 1149) for digital avionics are well advanced. Analog, RF, and EO electronics can be monitored both with dedicated sensors such as power meters on transmitters and by analysis of output data to assess performance. RF and EO sensors can be calibrated using reference patterns that are either printed on the inside of radomes or moved into the field of view (FOV). Engines are already heavily instrumented for performance optimization, and additional sensors for such things as vibration and oil contamination could enable very thorough health checking. For example, an acoustic monitor might detect changes in the frequency content of engine noise associated with incipient blade cracks, and external engine oil monitors like the spectroscopic oil analysis program (SOAP) might be replaced by built-in contamination monitors.

  An intriguing possibility for both metallic and composite aircraft structures is the use of embedded strain gauges to monitor structural integrity; changes in strain patterns under well characterized flight loads could provide valuable fatigue and damage information. Cooperative sensing among aircraft might be a convenient means of evaluating RCS degradation. A host of other possibilities exists, including:

  - Measurement of voltage and transients on aircraft electrical power circuits.

  - Differential pressure measurements to determine when filters need replacement.

  - Position sensors for actuators to check on such things as flap rigging.

  - Contamination sensors in fuel tanks.

- **Portable, Automated Inspection Instruments (PAIINs).** Some aspects of health and status monitoring are probably impractical to implement entirely with embedded instruments. However, we see great potential in the replacement of current inspection techniques with smaller, cheaper, faster, less manpower-intensive methods. Extensions and combinations of known sensor phenomenologies, especially those that require no disassembly or chemical treatment of the structure, are important here. Airframe fatigue and corrosion might be detected with a set of lightweight ultrasonic instruments that stimulate an airframe or other structure and measure the resulting signatures at carefully

chosen points. Manual engine borescoping might be replaced by an automated instrument. There is great potential in the use of small, highly intelligent robots that crawl over and through structures to make a variety of measurements.

- **Multispectral Robotic Vision**. A substantial body of technology exists for automated inspection of objects, for example, to determine orientations on a conveyer belt. Sensing with higher degrees of dimensionality has great potential in the overall area of materiel handling and inspection as a component of highly automated and adaptive handling and shipping systems. Such instruments could perform physical mensuration, assessment of coatings and preservatives, and even verification of constituent materials, at least in the sense of comparing measured signatures to stored calibration patterns. Both in complex depot inspection stations and in portable instruments for deployed operations, such techniques could improve logistics management and reduce manpower requirements.

4.8.4 Enabling Technologies

Achieving the vision for embedded system monitoring and diagnosis depends mainly on the availability of inexpensive microsensors with high sensitivity and selectivity for the variables of interest. Silicon and other semiconductors offer a wide array of sensing mechanisms for temperature, mechanical displacement, stress, chemical species, voltage and current, and other variables, combined with the ability to embed signal conditioning and data processing functions in the sensing unit and the potential for low cost batch fabrication.

BIT/FIT for digital avionics can achieve performance on the order of detection of 99 percent and isolation of 98 percent of naturally occurring failures with a modest level of additional hardware and software. Progressively lower, but still highly effective, levels of diagnostic precision are possible for analog and RF/EO hardware using embedded calibration and test signal generation and computer monitoring of outputs. The value of these methods is multiplied by small, highly integrated multifunction sensors for environmental variables (temperature, g-forces, supply voltage, etc.).

Table 4-7 lists candidate sensor phenomenologies for structural integrity monitoring. Techniques with great promise to yield significant improvements include swept frequency eddy current measurement, high resolution real-time radioscopy (HR-RTR), and advanced pattern recognition algorithms, including neural networks, to extract precise problem diagnoses from the complex signatures produced by such instruments.

Complementary data processing techniques, mainly using artificial intelligence, can extract the maximum information from patterns of sensor outputs. Micromachines and robotics will enable the replacement of large, fixed external instruments with small, mobile, and highly portable surveillance platforms. The synergistic application of these technologies will make practical a philosophy of system design and support in which aircraft, munitions, and other assets contain the means for status monitoring and diagnosis of failures and damage, greatly reducing the requirement for external test equipment and maintenance technicians.

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Table 4-7. Typical Phenomenologies Applied to NDI/NDE/NDT

NDI/NDT/NDE Category	Applicable Phenomenology
Corrosion	Eddy Currents Ultrasonics Thermal Imaging Shearography Acoustic Emission Enhanced Visual Inspection
Cracks	Magneto-Optical Imaging Radiography Enhanced Visual Inspection
Disbonding/Delamination	Ultrasonics Radiography

4.9 Summary of Operational Tasks and Sensor Concepts

The operational tasks and the sensor concepts have been presented in a mission-to-task-to-concept structure. The operational tasks are meant to establish a framework for consideration of the sensor concepts and technologies. The enabling technologies show a great deal of commonality across the various operational tasks. Table 4-8 summarizes the key enabling technologies that emerge from this analysis.

Table 4-8. Enabling Technologies

Operational Task	Enabling Technologies
Battlefield Situational Awareness	RF Conversion Moderate Power Tunable Lasers High Efficiency Solar Cells Mass Storage Devices Intelligent Agents High rate, Highly Linear Analog-to-Digital Converters Fusion/Correlation Techniques Automatic Target Recognition
Surveillance of Weapons of Mass Destruction	Multispectral Laser Radar for Effluent Detection Low Cost Focal Plane Arrays Micro-Machinable Electromechanical Systems Materials Tagging Adaptive Tasking Information Fusion/Correlation Femtosecond Laser Radars Unattended Ground Sensors (Acoustic, RF, IR, Seismic)
Surveillance of Underground Facilities	RF/Seismic Sensors With Tomographic Processing Multispectral Laser Radar for Effluent Detection Unattended Ground Sensors (Acoustic, RF, IR, Seismic) HF/VHF Synthetic Aperture Radar Weapon Borne Battle Damage Assessment Sensor
Accurately Deliver Munitions	Multifunction EO/IR Modular, Multifunction RF Components 3-D Laser Radar Miniature, High Accuracy Inertial Measurement Unit Imaging IR Sensor Multispectral Laser Radar Automatic Target Recognition Weapon Borne Battle Damage Assessment Sensor
Find Theater Ballistic Missiles and Cruise Missiles	Space Based Radar High Energy Lasers Optical Fire Control System Unattended Ground Sensors (Acoustic, RF, IR, Seismic) HF/VHF Radar
Special Operations and Military Operations Other Than War	Miniature Focal Plane Array Chem Lab On a Chip Multispectral Apertures RF Sensors Multispectral Laser Radar for Effluent Detection Unattended Ground Sensors (Acoustic, RF, IR, Seismic)
Force Sustainment	BIT/FIT Sensors Corrosion Sensors Crack Detection Sensors Disbonding/Delamination Sensors

5.0 Illustrative Sensor System Concepts

5.1 Improved Sensing Through Integrated Operations

In order to give a flavor of the changes, some radical and some evolutionary, that will occur as advanced technologies are introduced, we present in this section a set of system concepts to address difficult sensing challenges like those raised in Section 4. Improvements in sensor system capability will come about in two fundamental ways. First, almost any type of sensor offers opportunities for improvement in performance, reliability, and cost through the use of better materials and designs. The second and far more powerful approach involves the integration of multiple sensors in an information fabric that achieves high levels of dimensionality and target coverage. The basic issues of a "system of systems" architecture were discussed in Section 2. This overall theme of sensor internetting and cooperative operation underlies much of our thinking about the future of sensor systems.

For any given sensor task, there are innumerable potential system solutions. Our purpose here is not so much to prescribe in detail the systems and networks the Air Force should pursue as to stimulate thinking about innovative ways to apply technology to solve operational problems and to suggest ways in that future sensor systems will differ from today's inventory. The overall goal in constructing these concepts is to leverage technology opportunities in ways that are feasible and affordable while yielding major improvements in capability. We seek new ideas that will capture the power of advanced technology while at the same time ensuring that concepts are consistent with technologies that will be available in the time frame of *New World Vistas*. In each of the following subsections, an illustrative concept is described in terms of the elements and functions of the conceptual system and a discussion of the enabling technologies needed to implement it.

5.2 Summaries of Concepts

The following paragraphs describe seven widely varying concepts. They have in common the ideas of applying multiple sensing mechanisms (high degrees of dimensionality), powerful algorithms and processors, and extensive integration of systems and functions.

5.2.1 Concept 1—Target Reporter

5.2.1.1 Overview

This concept speaks to the use of advanced sensors and platforms to achieve timely, comprehensive situational awareness of the battlespace. A UAV maintains a 72 hour on-station orbit, providing continuous surveillance of key LOC (roads, canals, rivers, ports, rail lines) segments (passes, intersections, bridges, choke points) over a large battle area (200 by 400 nm), using automated ESM, MTI and UGS coverage of those key points. Spot SAR sensors are used to map segments for which analysis indicates targets. An ATR subsystem identifies traffic to verify activity and validate analysis, and report targets. The UAV broadcasts traffic and target reports for mission planning and execution functions. Figure 5-1 depicts the concept.
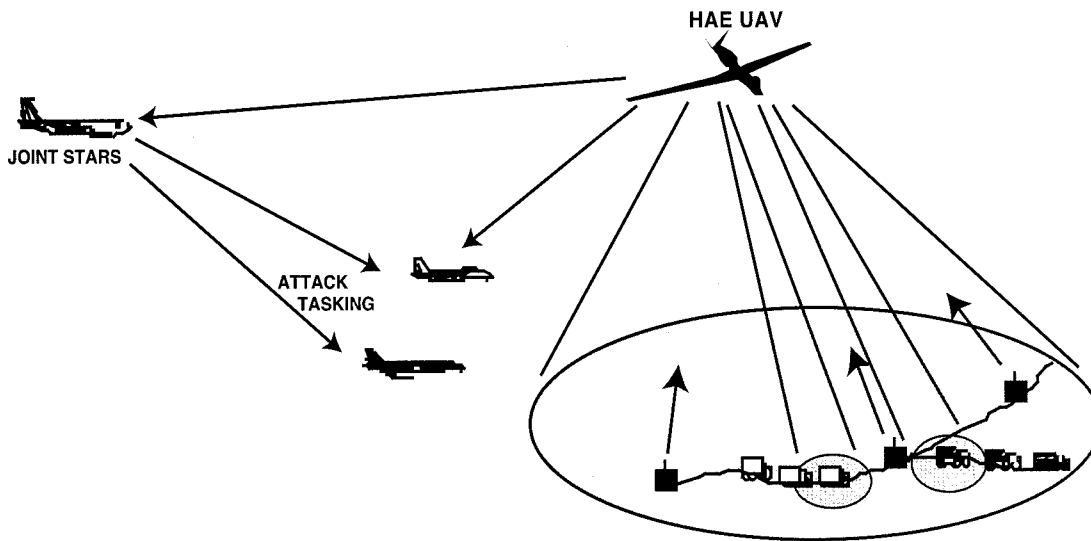
Figure 5-1. The Target Reporter Concept Supports Dynamic Battle Command and Control

5.2.1.2 Sensor Concept

The Target Reporter provides direct support to military operations by providing high accuracy target identification, location, and context to the battle control elements and to the shooters at very low communications data rates and with few false alarms. Targets include fixed target activity, mobile targets, and targets obscured by foliage or other types of camouflage, concealment and deception (CC&D). It supports the Air Force missions of Suppression of Enemy Air Defenses (SEAD), Offensive Counterair, Interdiction, Close Air Support (CAS), Surveillance and Reconnaissance, and Special Operations, including MOOTW.

The Target Reporter sensor system suite includes advanced sensors to accomplish the elements of its mission:

- **(UAV).** The UAV for this target reporter concept is a high altitude endurance (HAE) platform with a 72 hour on-station time at 65,000 feet or higher altitude, a gross weight of 30,000 lbs and a payload capacity of 4000 lbs. It is based on advanced propulsion technology and lightweight structures.

- **ESM.** The ESM system is used to detect, analyze, and locate electromagnetic emissions associated with military operations. This could include radar emissions associated with air defense systems, communications emissions associated with command and control, and general emanations associated with air and ground weapons. The ESM provides moderate accuracy of location, sufficient to cue the imaging sensors to provide more accurate identification and location data. ESM also provides essential elements of target classification and identification.

- **MTI Radar**. The large aperture MTI radar, including ground moving target indicator (GMTI) modes for vehicle targets, provides a situation picture of a large battlespace (200 nm range) to present the commander with the "big picture." Moreover, the MTI radar would be cued to frequently or continuously observe key segments of lines of communication (road intersections, runways, heliports, marshaling yards, rail lines, etc.) for activity to compile time histories from which activity patterns can be analyzed and future actions predicted. In addition, the analysis of the MTI returns offers moderate accuracy target identification and moderate accuracy location of potential targets in order to cue the imaging sensors.

- **UGS**. An internetted wide area network of air-delivered and air-monitored unattended ground sensors (see Section 5.2.2) would be multiphenomenological including acoustic, seismic, and magnetic based transducers, and the associated sensor processing. The UGS system could also be covertly seeded at critical movement points or at facilities from which personnel or vehicles could depart. Sensors would classify targets and report to the UAV via a low-probability-of-intercept (LPI) communications link.

- **SAR**. The synthetic aperture radar will provide broad area coverage (5 km by 5 km) at moderate resolution and will adaptively provide focused imaging at high resolution (down to 0.3 m) when cued by analysis of wide area images or by other sensors such as ESM and MTI. High resolution imagery will support target location with an accuracy of 10 m as well as a major source of data for target identification. For general imaging, X-band is probably optimal, while the desired capability to penetrate foliage suggests selection of a wide bandwidth VHF frequency. Technology advances allow progress toward broadband and eventually multiband radars.

- **ATR**. The automatic target recognition provides analysis of MTI, UGS, and SAR returns to provide accurate determination of the target class and identity. It makes use of existing information on the environment (terrain, weather, urban activity, etc.) provided to the system in advance, and uses model-based vision techniques for accurate targeting decisions. Much of this processing is performed onboard the Target Reporter to speed up the overall engagement loop from target detection to strike and to reduce the transmission of low-content raw data to higher fusion centers.

- **ASC**. The automatic sensor cueing capability provides analysis of MTI, ESM and UGS returns to provide accurate cueing of the imaging SAR to a suspected target or situation. It exploits analysis of single and multiple sensor returns.

5.2.1.3 Enabling Technologies

The Target Reporter, with the individual sensor concepts discussed above, requires the development of many sensor and supporting technologies. Some are:

- Lightweight, low cost radar apertures with broad bandwidth (600 MHz) that are tunable over at least an octave, high DC-RF conversion efficiency, and excellent beam control (e.g., multiple null steering to defeat jamming).

- ATR algorithms and compact, high performance processors that optimally combine the full range of available sensor data streams for high quality target detection in clutter and real time classification or identification.

- ASC algorithms for MTI radar, ESM, and UGS returns.

- Micro-miniature, internetted, unattended ground sensors (see Section 5.2.2).

- Robust, LPI, anti-jam data links for bitways among Target Reporter platforms, other C^3I nodes, and attackers.

5.2.2 Concept 2—Integrated Arrays of Distributed Unattended Ground Sensors

5.2.2.1 Overview

Many difficult information collection tasks can be attacked by "saturating" a facility, an area, or an entire theater with small sensing devices equipped with a variety of detectors. These units are often most effectively seeded by aerial delivery systems and monitored by aerial relay platforms such as UAVs to keep data link ranges short. These devices will use low power microelectronics and simple, but robust, data links to hold down size, power consumption, and cost. Detectors for acoustic, seismic, chemical/biological species, ESM/SIGINT, magnetic, and possibly other variables can be combined in a UGS package for specific applications. UGS can be used to monitor facilities such as NBC weapons sites and command centers, to report vehicle traffic and in some cases to classify individual vehicles, and to do many other subtle and diverse sensing tasks. They are inherently covert, and a UGS array is robust in that discovery and removal of individual units by the enemy represents only a fractional loss of capability. Figure 5-2 illustrates a typical scenario in which a variety of UGS monitors a hardened facility and the traffic on a road.

5.2.2.2 Sensor Concept

Microsensors can be integrated with a variety of packaging and mobility schemes. The concept envisions extensive use of unattended ground sensors, including both fixed packages and small flying or crawling mechanisms able to penetrate hostile facilities. For maximum effectiveness and affordability, a set of modular detection elements for various variables (sound, seismic vibrations, chemical species, RF signals, etc.) would be mixed and matched in a given package for a specific need. See Section 5.2.3 for a fuller description of the use of such sensors to measure buried structures. Among the many other situations in which this concept has great potential are detection of trace effluents associated with NBC facilities and ESM/SIGINT interception based on placing receivers very close to communication systems and lines.

As important as the sensors themselves are the methods for collecting and exploiting the data they produce. Individual sensors will report activity in a manner much like cellular telephones going from one repeater cell to the next. Rough tracks and target counts can be derived along with the characteristics that help identify targets. This data will be fused and assessed with other sensor outputs, intelligence, and other information and presented to commanders, controllers, and shooters in support of situational awareness, planning, and engagement control.
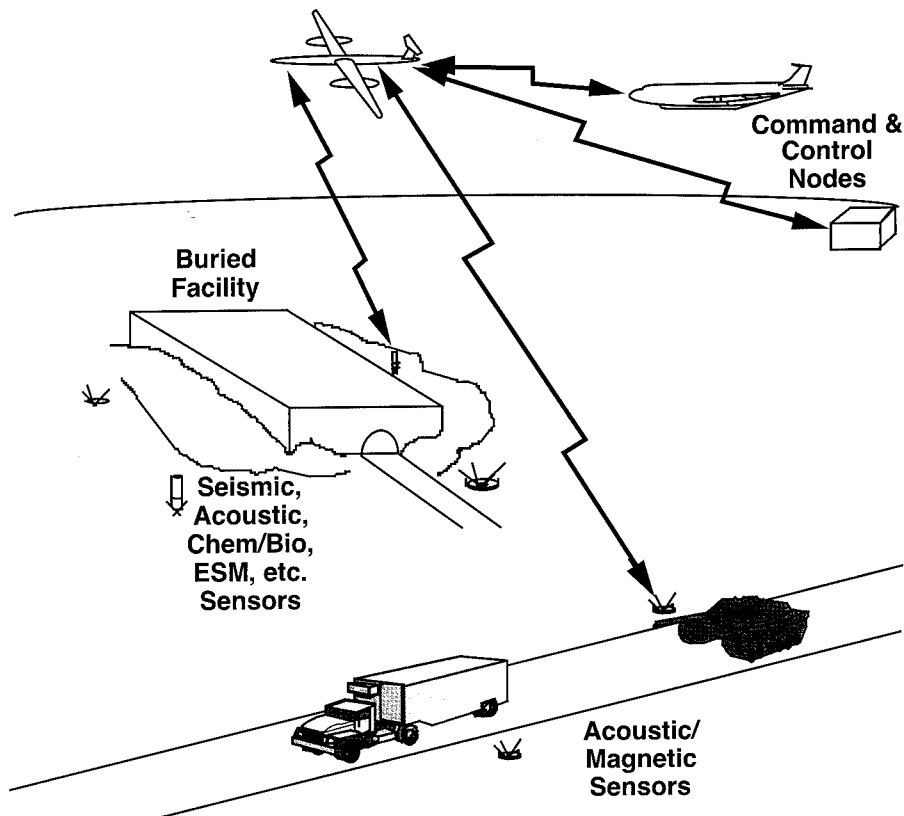
Figure 5-2. Typical Uses of Microsensors With Multiple Detector Types
Include Covert Surveillance of Facilities and Monitoring Traffic

5.2.2.3 Enabling Technologies

Although many components of microsensors like those described in this concept are available (e.g., miniaturized RF transceivers, acoustic sensors, etc.), a number of technology improvements affecting both packages and detectors are key to successful implementation. These include:

- MEMS as a basic method of designing and fabricating many kinds of microsensor structures and actuators.

- Very low power, LPI data links with matching relay packages for UAVs and other platforms.

- Very high energy density batteries.

- Sensitive, high resolution sensing elements, especially for variables with no commercial equivalent such as chemical/biological agents.

- Effective algorithms for fusing microsensor data with other sources and for flexible, easily interpreted information display.

5.2.3 Concept 3—Underground Target Surveillance

5.2.3.1 Overview

In this concept, a UAV maintains surveillance of known underground facilities containing such activities as NBC production and storage, high echelon command and control, weapon storage, and general equipment storage. Structures will normally include tunnels, buildings, and caves, but might also include the rubble of a destroyed building. Capabilities associated with counter-drug and counter-terrorist below-ground surveillance are also highly important.

The system concept, shown in Figure 5-3, while primarily employing a UAV, also includes off-board sensors. On the UAV, the sensor system would consist of a multispectral EO sensor with active and passive modes (e.g., differential absorption laser radar) to detect and identify effluents, a spot synthetic aperture radar, and a seismic tomography stimulator. Off board (and linked to the UAV) would be an air-seeded UGS array associated with the seismic tomography concept and, when appropriate, other UGS types such as acoustic traffic and activity monitors, ESM collectors, and ground-level chemical/biological agent detectors.

SAR & IR
DIAL

SEISMIC
STIMULATOR

A - Seismic Tomography UGS
B - Acoustic/Seismic/Magnetic UGS
C - Effluent/Agent UGS
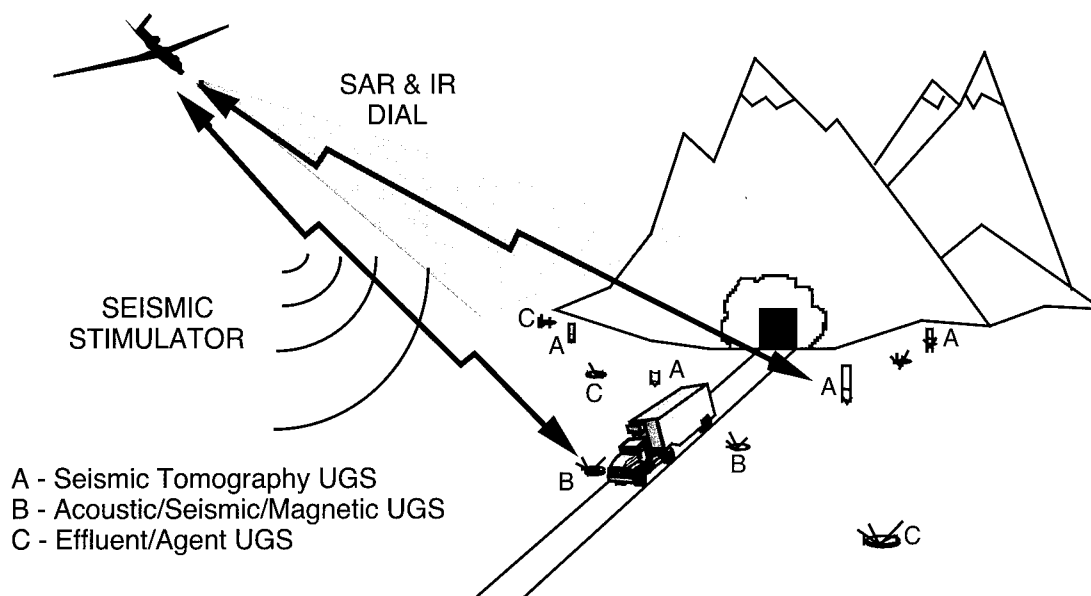
Figure 5-3. Underground Target Surveillance Concept

5.2.3.2 Sensor Concept

This concept brings a variety of sensor and platform technologies together to deal with the difficult and growing problem of buried and hardened facilities. The surveillance of underground facilities is key to monitoring and targeting the activities of enemy leadership, detecting and classifying weapons manufacture and storage (especially NBC materials and weapons), and locating and classifying command and control sites. It is also essential to tracking transfers of personnel (including captives), weapons, and other equipment and to dealing with many counter-terrorism, drug interdiction, and similar tasks.

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The concept includes the following sensors:

- **DIAL**. The DIAL sensor has the capability to be cued to underground facility locations and to analyze effluent gases by differential absorption of the return associated with the transmission of two or more laser lines (wavelengths). The active sensor can be supplemented with multi- or hyperspectral passive sensors to extend the range of chemicals detected.

- **RF/Seismic Tomography System**. The radio frequency/seismic tomography system uses a bistatic approach in which either or both electromagnetic and seismic waves are transmitted from the UAV into the ground to be received by implanted UGS in a tomographic scheme to construct a three-dimensional map of the electromagnetic and seismic properties of the volume observed. The stimulator could also be a natural noise (like thunder), an independent generator (like a bomb or gunfire), or a "thumper" implanted as part of the UGS array. Seismic waves respond to mechanical (elastic) properties of the volume, while electromagnetic waves respond to the electrical properties. The combination of returns, carefully processed, provides a knowledge of the construction layout of the facility and could, on the basis of change detection, detect the movement of personnel and equipment. Actual Doppler detection might sense finer details of the movements of equipment and personnel.

- **Spot Synthetic Aperture Radar**. The UAV's SAR is used to image the underground facilities adits, as cued by other sensors, either on-board (DIAL, etc.) or off-board (UGS and Tags), to provide immediate identification of the specific activity at the facility.

- **UGS Array**. In addition to the seismic sensors, a complementary UGS array, delivered and monitored from the air, tracks activity related to entering and departing the underground facility. Sensors allow vehicles to be classified, providing information on materials movements and possibly even arrival or departure of key personnel, especially in conjunction with ESM and tapping of landline communications. Other UGS can be used to detect trace quantities of effluents associated with the production of weapons, or the operation of command and control centers. These sensors can also be used to detect very small quantities of chemical or biological agents that leak from facilities or storage. UGS can also be used to trigger events (turn on beacons, change codes on tags, etc.) that can aid subsequent surveillance and tracking operations.

- **Tags**. Tags can be used to actively or passively provide tracking of vehicles and personnel on which those tags have been implanted, overtly or covertly. The tags can be implanted in equipment upon manufacturing, into raw materials at growth or mining, or onto vehicles and equipment later (decals, retroreflectors, fuel tank caps, gifts, placards, batteries, replacement tires, etc.) The location or activity could be determined by polling the tags from the UAV. Tags could also be placed in food or water supplies for the purpose of tracking the flow of such supplies, and hence determining the layout of the facility, or the location of personnel.

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5.2.3.3 Enabling Technologies

The key enabling technologies for the Underground Facility Surveillance concept are:

- UGS seismic tomography devices and processing methods derived from extensions of technology used in minerals exploration, scientific seismology, medical diagnosis, and other three-dimensional materials imaging applications.

- Micro-miniature transponding tags with data storage and LPI transmission capability, and suitable for long range operation.

- Automatic analysis of DIAL (effluent spectroscopy) and multi- or hyperspectral EO signatures to determine activity, detect chemical/biological materials and agents, estimate numbers and types of personnel, evaluate status of personnel and equipment, and so forth.

- Chemical and biological detection sensors such as conductive polymers and enzyme-based electro-chemical technologies suitable for UGS and other applications.

5.2.4 Concept 4—All Condition Concealed Target Detection

5.2.4.1 Overview

Detection of fixed and mobile targets that employ CCD is a difficult task and one in which integrated multisensor operation has great power. Furthermore, it is essential that we be able to find, track, and identify these targets under all conditions of day/night and adverse weather. Figure 5-4 sketches a typical scenario in which a mobile missile battery is concealed under trees. Of the many possible sensor combinations, the one shown involves a space-based wide area surveillance sensor, a cued UAV foliage penetrating sensor, and an unattended ground sensor with air and geophones to detect noise patterns associated with targets. Since the target is mobile, the engagement timeline may be short. We thus employ a C^3I platform such as Joint STARS as both the fusion center and the engagement controller. Target location is passed to an attack aircraft which launches a munition with some combination of geo-coordinate guidance and terminal homing and with a warhead matched to the target, typically an area weapon such as a submunition dispenser.

5.2.4.2 Sensor Concept

In order to deal with concealed targets, this concept includes a combination of multiple sensor types, including space-based, airborne, and ground units, backed up by sophisticated signature analysis and data fusion processes. Key elements of the concept are:

Exploitation of Multiple Target Signatures. The following are some of the sensor phenomenologies that contribute to detecting and classifying concealed targets.

- **Wide Area Surveillance Radar.** By detecting and tracking the locations and movements of hostile units over time, we can focus CCD-penetrating sensors on specific regions of interest. UHR SAR and GMTI radars on satellite or UAV platforms provide this all-condition surveillance and tracking.

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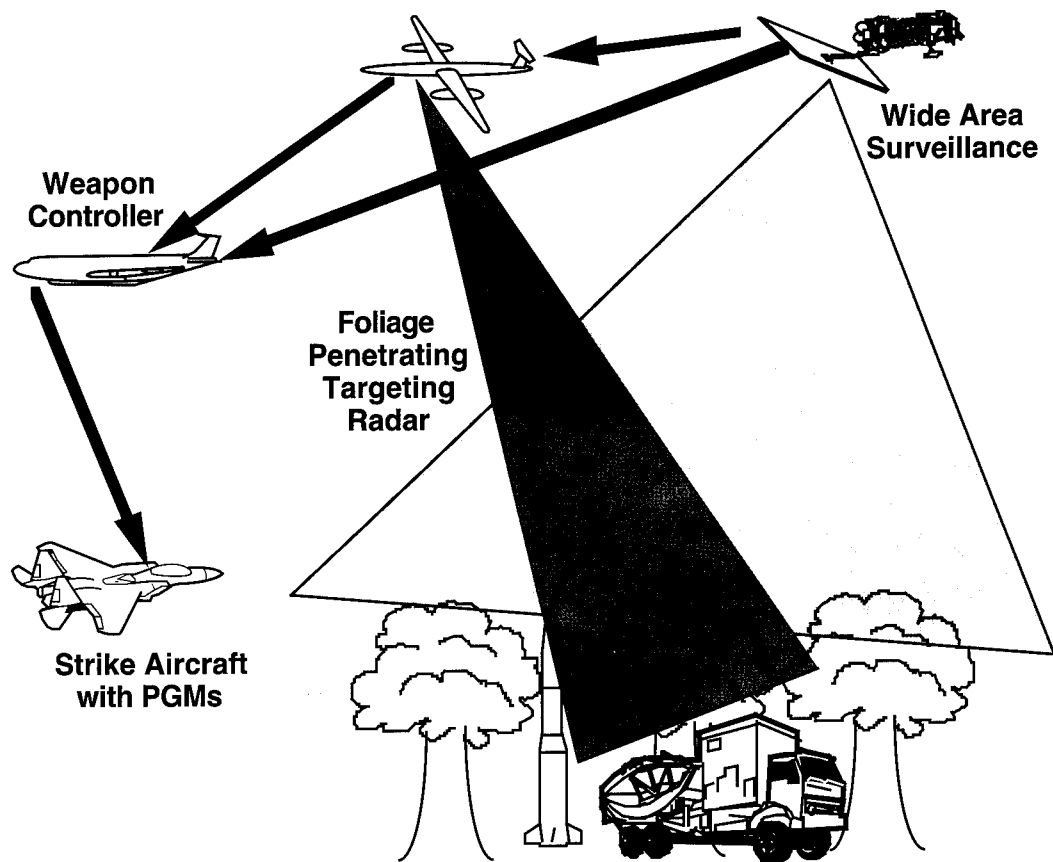
Figure 5-4. Typical Sensor Combination for Detecting Targets in Foliage

- **CCD-Penetrating Radar.** Foliage and many other CCD obstacles can be best penetrated at low radar frequencies. At the same time, target detection and classification requires high resolution, meaning broad bandwidth. A promising approach is thus a SAR sensor sweeping from, say, 20 to 600 MHz and mounted on a moving platform like a UAV to examine the area of interest from a wide range of angles to take advantage of primary reflection angles.

- **ESM/SIGINT.** Mobile targets will generally have to rely on RF communications that can be intercepted and exploited both for improved target location and classification and to provide warning of impending movements or attacks.

- **Imaging EO.** Although this concept stresses all weather capability, any information available from space or airborne EO imagers will be combined with other inputs both to track enemy movements over time and to improve the location and classification of targets. LADARs have some potential to detect subtle signatures such as foliage movements, and LIDARs may be able to detect engine exhaust or other emissions that betray the presence of concealed targets.

- **Ground Sensors**. In keeping with the complementary sensor concept of internetted, air-seeded UGS, we can use implanted acoustic sensors to monitor traffic at selected points and to listen for unique noise signatures associated with specific types of vehicles and equipment.

Near Real-Time Information Processing. Fast and effective signature extraction, target assessment, and fusion processing are essential to striking time sensitive targets such as mobile missile launchers or artillery. Our concept calls for distributed processing in which individual sensor platforms perform significant signal processing, feature extraction, and identification of targets or, at least, areas of interest, for example, by declaring the presence of man-made versus natural objects in a scene. Final data fusion is performed onboard an on-scene C^3I platform for speed and direct support to a weapon controller. The resulting solution is sent to a strike aircraft for prompt attack. Since CCD measures may defeat terminal seekers on munitions, the sensor solution may be required to provide precise target geo-coordinates to allow a coordinate guidance munition autopilot to put warheads within their lethal radius of the target.

5.2.4.3 Enabling Technologies

Each of the elements of the concept described above requires advanced technology to be effective. Some of these are available or will be in the near term, while others require significant development. Examples include:

- Affordable, lightweight, multimode space based radar sensors with significant onboard processing (see Section 5.2.7).

- HF wideband SAR radar and associated signature processing algorithms and hardware for penetration of foliage and other CCD.

- Affordable, covert UGS with embedded processing for recognition of specific acoustic signatures.

- Robust, LPI, jam-resistant data links with the necessary bandwidth for real time sensor data transmission.

- Data fusion algorithms and software capable of extracting high quality detection, location, and classification of concealed targets from a wide variety of real time data streams and historical information.

5.2.5 Concept 5—Weather Surveillance and Prediction

5.2.5.1 Overview

Even with all-weather high performance sensing and navigation, combat air operations will be significantly affected by weather. While the pictures of cloud tops familiar from current domestic weather satellites are useful, military aviators need accurate cloud and wind information at all altitudes. This concept addresses the need to provide highly accurate 6 to 12 hour forecasts, and greatly improved 24 hour and 5 day forecasts, anywhere in the world, especially over hostile territory where conventional weather observations are denied. It involves a variety of sensors on both satellite and UAV platforms which can deal with all combinations of cloud cover and winds. The concept also recognizes that ideal remote weather observing systems would almost

certainly be unaffordable, so that innovative uses of improved technology are essential. A mixture of EO techniques, which are precise but have limited cloud penetration, and radar, operating from multiple UAVs and possibly supplemented by satellites, delivers the data to construct an accurate "nowcast" and to drive high fidelity models that produce the required forecast. Figure 5-5 indicates the primary elements of the concept.
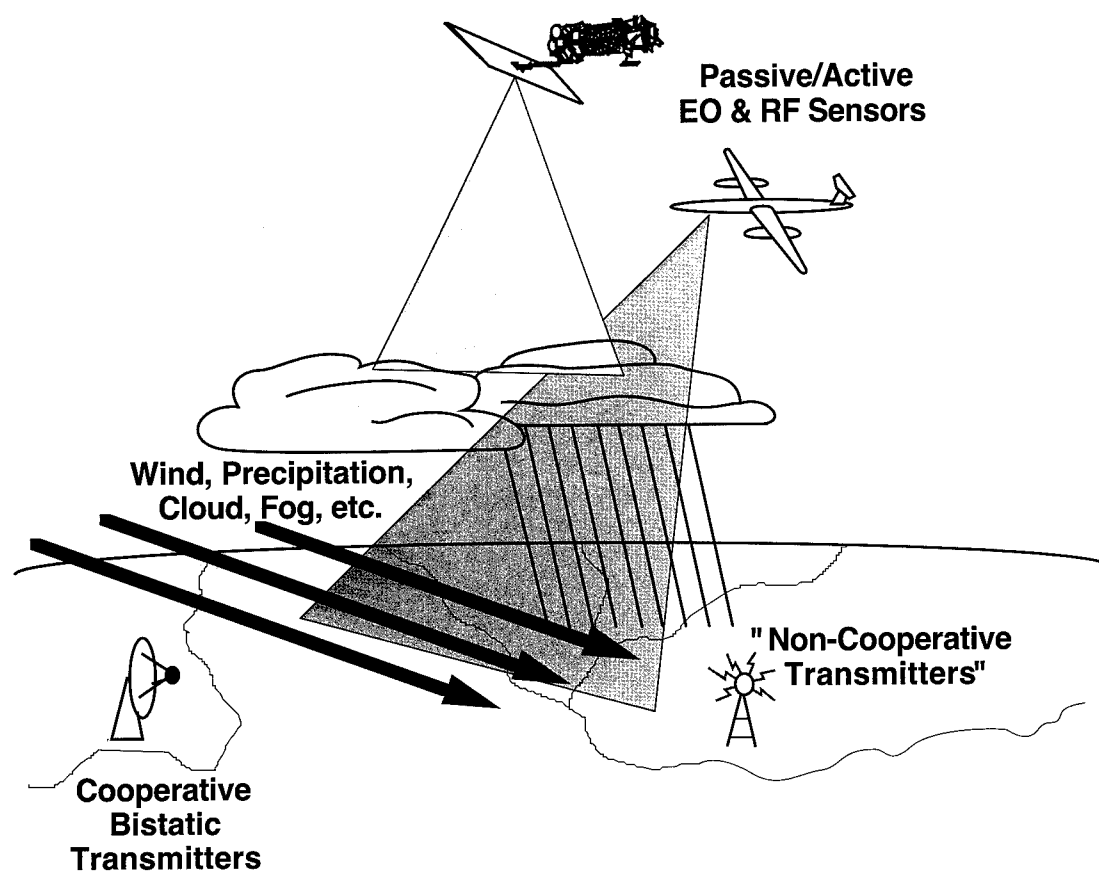
Figure 5-5. Multiple Sensors Contribute to Accurate Weather Awareness, Anytime and Anywhere

5.2.5.2 Sensor Concept

In order to make an accurate short-term prediction of weather over a given site, we need information on the synoptic evolution of weather patterns in the area over the previous 2 to 3 days as well as very precise knowledge of the current atmospheric state. Domestic weather forecasting relies on regular rawinsonde launches to collect data at various altitudes, supplemented by Doppler radar, meteorological satellite data, reports from aircraft in flight, and ground station readings, as input to predictive models. Atmospheric models and computing power have improved to the point where forecasting accuracy is limited mainly by the accuracy and spatial/temporal spacing of these readings. The primary variables of interest are temperature, dew point, pressure, wind speed, and wind direction at various altitudes.

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Since we require remote sensing over denied territory, a very different approach is in order. Four general sensor types, which can be carried on satellites, high altitude aerial platforms, or both, are candidates for inclusion:

- **Passive IR**. Sensors with high resolution FPAs (benefiting from DoD investment in forward looking IRs [FLIRs] and other sensor systems) and sensitivity at multiple near, mid, and long IR wavelengths where there are atmospheric transmission windows and phenomena that yield useful information (e.g., water vapor absorption near 1.1 μm and CO_2 bands near 4.3 and 15 μm) provide information on water vapor, atmospheric temperature, surface ice, and other variables of interest when cloud conditions permit. IR resolution is inherently higher than microwave sensors can achieve but becomes progressively less useful as cloud cover increases, especially in layers.

- **Passive Microwave.** Radiometers operating from about 1 GHz through sub-millimeter wave bands can be used to image surface characteristics and clouds at frequencies below 90 GHz, temperature using the 60 GHz CO_2 line, and water vapor using the 183 GHz water line. Propagation through cloud is such that these sensors can map cloud tops and bottoms of multiple layers up to fairly high cloud densities. Synthetic Aperture Radiometry has been proposed as a way to improve horizontal resolution and to improve interpretation of data in the presence of liquid water in the atmosphere. Vertical profiling resolution is presently very limited and might require revolutionary techniques such as sensing occultation of GPS signals.

- **LIDAR**. Active EO sensors detect backscatter from atmospheric aerosols and can exploit a variety of phenomena, including fluorescence, depolarization, and DIAL to profile temperature, moisture, winds, pressure, water vapor, thin cloud tops and bottoms, aerosols and trace chemical species. They will operate at wavelengths longer than 1.5 μm. Like all optical techniques, they lose effectiveness as cloud density increases but have excellent resolution. LIDAR looks promising for detection of atmospheric turbulence through extension of techniques for measuring wind velocity.

- **Radar**. Radar systems on satellites or high altitude UAVs, typically operating in the range of 20 to 100 GHz, have the potential to provide cloud surveillance over broad areas and to penetrate essentially any multilayered cloud condition. Innovative approaches include tailored waveforms and more powerful data processing, especially high sampling rates, to improve discrimination of cloud returns from ground clutter and other interference. It may also be possible to use bistatic modes, including illumination from sources of opportunity such as radio and TV transmitters.

5.2.5.3 Enabling Technologies

Many technologies contribute to small, affordable, high precision, long lifetime weather surveillance sensors. Examples include:

- **Optical Sources**. The LIDAR portion of this concept relies on lasers and associated cryocoolers that are small, efficient, and highly reliable at the wavelengths of interest, especially mid- and longwave IR. Eyesafe solid state lasers are important for applications such as DIAL.

- **LIDAR and Passive EO Detection and Processing**. Sensitive, multiwavelength receivers, advanced signal processing for temperature profiling and other measurements, and sensitive Doppler modes for wind and turbulence resolution are all necessary to achieve the desired performance in affordable systems. These systems can benefit from materials, manufacturing, FPA design, and other technology improvements in the broader field of EO sensors. In addition, the inherently broad coverage of weather surveillance generates enormous volumes of data, making powerful onboard processing to extract features and reduce the volume of raw data to be transmitted extremely valuable.

- **RF Sources**. Efficient, high power sources at 94 GHz and above are needed for weather surveillance radars that can exploit all the phenomena of interest.

- **Phased Array Radar**. Extremely broadband radars, including large deployable antennas for satellites and designs suitable for high altitude UAVs, are needed to complement EO sensors to achieve the required capability. Development of Synthetic Aperture Radiometry has promise for improving the performance of passive RF imaging sensors.

- **Dual Use Technologies**. Despite the significant differences in their operations, military and civilian weather systems have much in common, and this synergism should be exploited to reduce development and acquisition costs.

5.2.6 Concept 6—Modular, Integrated, Multifunction Phased Array Based EO System

5.2.6.1 Overview

This concept deals with higher performance and more affordable ways to meet the continuing need for high performance EO systems on attack aircraft and other platforms. EO systems are important for functions that include situation awareness/threat warning, navigation and pilotage, A/A and A/G targeting and FC, and support for weapons such as laser-guided bombs. Additional potential applications include covert data links and improved IFFN. Future weapon systems need sensors with improved ability to penetrate weather and battlefield obscurants, more precise target location and identification, and improved compatibility with LO, all at reduced cost.

The major cost for most EO systems is in the gimbals and the precise pointing and stabilization. This is a body-fixed concept, with no gimbals and no mechanical stabilization. It is a modular design as sketched in Figure 5-6 that uses optical phased arrays for beam shaping and pointing analogous to a phased array radar. It also is a multifunction concept that has the potential to incorporate any or all of the functions listed in the figure.
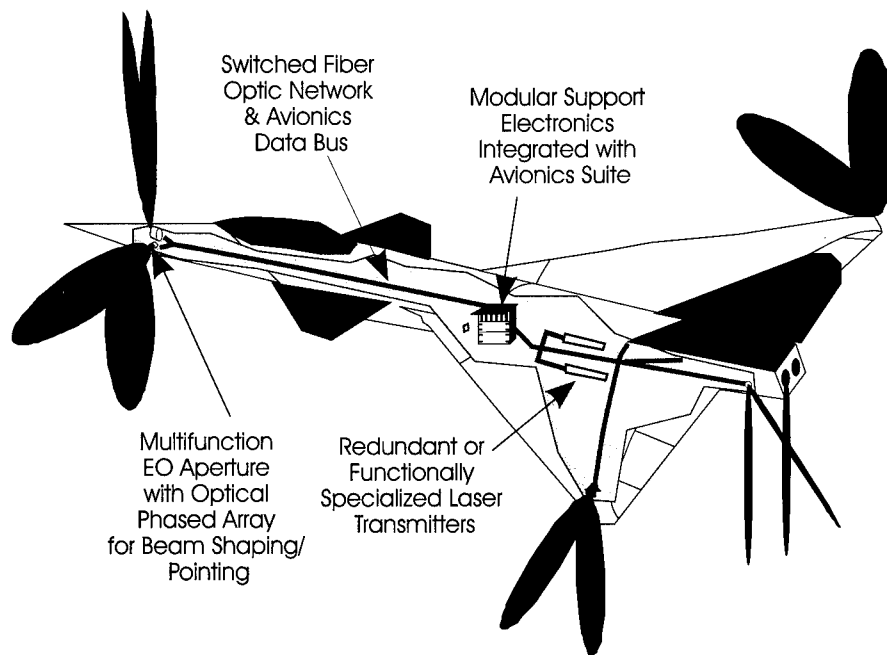
Figure 5-6. Integration of Multiple EO Functions in a Modular Sensor

5.2.6.2 Sensor Concept

The concept includes four to six apertures around the aircraft to provide 360° azimuth and top and bottom apertures, if required, for 4π steradian coverage. Each sensor module is a cylinder roughly 12 cm in diameter, with a 10 cm optical aperture, and roughly 20 cm deep. One or two system modules will be required as part of the plane's integrated avionics suite, connected to the aperture modules through fibers. There will be at least two laser transmitters, linked through a fiber switching network to each of the modular apertures. A single laser should be sufficient for designator and targeting functions, except for redundancy considerations. The network will allow any laser to transmit through any aperture. Laser transmitters should be capable of IRCM. A high rep rate, high duty cycle transmitter will be needed for covert high bandwidth communications. Primary laser receivers will be in individual aperture modules, although special purpose receivers could be centrally placed with signals sent over the fiber optic network.

The IR receiver will be a staring, microscanned sensor. Passive sensors can use a high field rate and an inertial system, so electronic stabilization and antialiasing will be used for low cost. One approach would be to combine a narrow FOV staring IR sensor with an optical phased array for wide angular coverage. This should allow target tracking to a fraction of a milliradian (called the detector angular subtends, DAS). Detailed processing would only occur in the region of a cue, provided by another sensor. Target acquisition accurate enough to put a laser designator on the target would then be used to deliver a laser-guided munition. The designator will be a low rep rate 1.06 μm solid state laser. The LADAR/target ID source will be a 1.5 μm laser system with direct detection. It will use high range resolution, two-dimensional angle/angle imaging, or three-dimensional imaging, for target ID. Missile warning will require wide FOV capability.

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5.2.6.3 Enabling Technologies

A number of critical technology developments will influence the eventual shape of this system concept. Some of these are:

- **Optical Phased Array Technology.** We need to steer the laser beam rapidly over a 60 deg by 60 deg angular area for a 6 aperture concept, or 90 degrees x 60 degrees for a 4 aperture concept. Steering efficiency should be close to the cosine limit approached by microwave phased array radars. We also want to steer a narrow FOV passive sensor with the phased array.

- **Electronic Stabilization and Random/Natural Microscan.** Image stabilization is needed to eliminate aliasing artifacts in an image.

- **Fiber Optics.** We need the ability to transmit an image through a single fiber by inserting it and removing it at a focal point. This is easier for narrow-band laser images, since fiber dispersion will not be as much of a problem. This determines the location of array laser detectors, or passive broadband FPAs.

- **Clutter Rejection.** We also need the ability to remove A/A infrared search and track (IRST) clutter using large DAS, with rapid readout and electronic stabilization providing random sampling at higher angular resolution (e.g., 1 mrad DAS, 480 Hz readout, estimated sampling every 150 μrad or so based on random motion). If we can steer a narrow passive FOV, higher angular resolution will be available. Sensor data quality must support adaptive spatial/temporal processing to extract faint targets in severe clutter.

- **Pixel Ganging.** We need the ability to gang together pixels in an image for readout and processing purposes, and to focus on detailed readout of only selected portions of a focal plane array.

- **Multifunction Apertures.** We need the ability to conduct all functions through all apertures using the combined power of optical phased arrays, advanced FPAs, multifunction laser transmitters, switched fiber optic networks, and other elements of this concept.

5.2.7 Concept 7—Low Cost Space-Based Surveillance

5.2.7.1 Overview

This concept is based on a mix of high resolution radar sensors and imaging EO sensors on small satellites to provide a launch-on-demand capability to place a tailored constellation on orbit over an area of interest. When a crisis erupts, the first source of information is likely to be national assets and the historical database, followed a few hours later by information collected by manned aircraft available at sites local to the crisis. As soon as a day later, continuous coverage might be available from UAV's deployed from CONUS and based as close as possible to the theater of interest. If a crisis is anticipated to last for an extended period (more than 30 days or so), it might be economical to deploy a space based constellation of low altitude surveillance satellites that would be capable of providing near continuous coverage within the theater. If UAVs must operate at long ranges from friendly bases (say more than 200 nm), the cost of

operations to achieve continuous coverage, overflight requirements, and reliable data downlinking all become more challenging. Pre-existing space-based sensors are unlikely to provide the level of coverage needed.

We envision a LEO constellation of 10 to 20 satellites in the proper orbital planes to achieve target coverage on the order of 10 minutes out of every 40 minutes. Using advanced but feasible sensor technology, reasonable production quantities, and a standard lightweight satellite vehicle bus launched on a single-stage-to-orbit booster, we can fly an individual satellite for as little as $25M with a lifetime of perhaps six months to a year. During time away from the target, each satellite downloads stored imagery, receives tasking, and orients and configures its sensor for the next pass. These assets operate as integral parts of the overall information gathering function, supporting surveillance, targeting, and warning functions with their data fused with other sources. Figure 5-7 summarizes the concept.
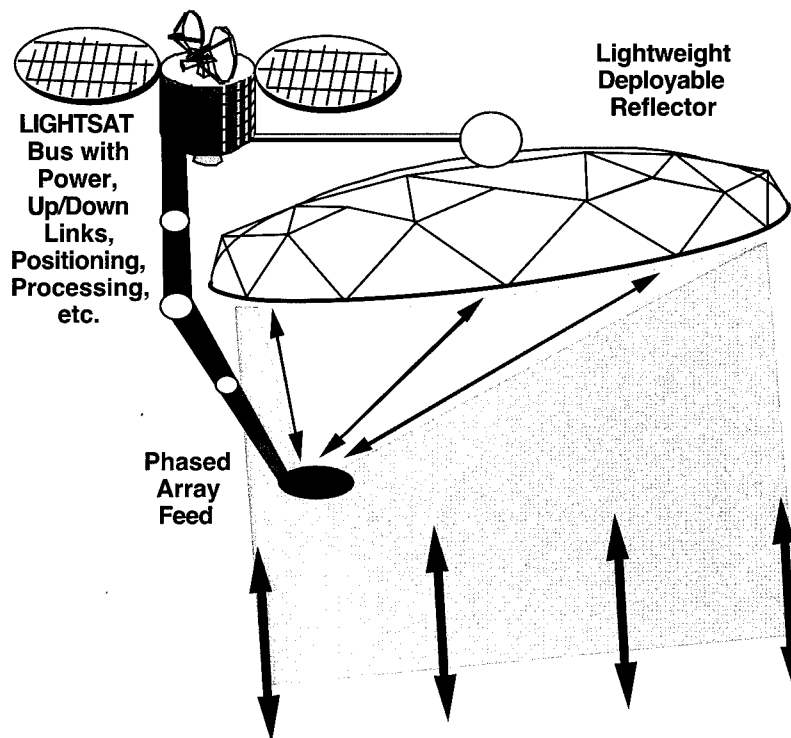
Figure 5-7. A Lightweight, Affordable Imaging Radar Satellite Can Provide Long Term, Tailored, Survivable Surveillance of an Area of Interest

5.2.7.2 Sensor Concept

To some extent, the crossover between continued use of UAV assets and launch of a satellite constellation will depend on the cost of the space assets relative to the operational costs associated with the airborne collection platforms. Thus the feasibility of space based surveillance depends on affordable satellites with suitable performance characteristics.

This concept uses a mixed constellation of SAR and optical imaging satellites, placed in 200 nm polar orbits by Pegasus or Taurus class boosters, and phased to provide short interval, near continuous coverage of a theater. A space-based surveillance radar satellite could provide better than 3 m resolution imaging and optical imaging satellites of the same weight could provide multispectral 1 m imagery in cloud free areas. At initial orbital altitudes of 200 nm, spacecraft lifetimes will be six months to about one year, depending on the level of solar activity. This light weight and short lifetime offer opportunities for innovative approaches to spacecraft design that may reduce the cost of the system. It may be possible to use commercial micro-electronics with relaxed total dose radiation tolerance since the orbit is low and on-orbit lifetime is short. Additionally, it may be substantially less expensive to depend on fault detection and automatic error correction rather than demanding high levels of redundancy for fault tolerance.

Interferometric SAR, change detection, and MTI techniques, combined with ATR, ASC and data compression techniques, will dramatically increase the utility of the collected imagery. Spacecraft maneuvering (hence propellant mass) can be minimized by orienting the bus and antenna for an entire pass, then leaving attitude constant during the pass. This will trade some amount of ground coverage for lower complexity and cost, while successive satellite passes can be tasked to deliver the required coverage.

5.2.7.3 Enabling Technologies

- A dominant cost element for high duty cycle space-based SAR is the solar power system. Continued progress in cost reduction of GaAs solar cells and associated concentrators, power converters, and batteries will be essential. However, for a low cost system focused on a single theater, low duty cycle operation allows a smaller power system to charge batteries during the 45 minutes of sun exposure per orbit. Thus the solar array can be less than half the size and cost of conventional designs.

- Lightweight, deployable antenna technology compatible with the LIGHTSAT bus is essential. Designs for high gain GEO commercial COMSATs may apply here. High efficiency, wide bandwidth T/R modules or power tubes are another area that will be critical to affordability. Technology drawn from a number of aircraft and ground radar programs contributes to achieving the required cost/performance ratio.

- Onboard processing will convert digitized I and Q channel data into images prior to downlinking. The primary obstacle today is the power consumption, size, and weight of the processor and very large associated memory (1012 bits per pass). Advanced high density three-dimensional semiconductor memories will be available, but low voltage, low power operation will be essential.

- Either the downlink must support very high data rates (Gbits/sec) or there must be a large buffer memory to store imagery for lower rate download. In either case, technology advances are needed to make the satellite affordable. Within the time frame of *New World Vistas*, it may be preferable to use dense, high performance processors to endow even low cost satellites with high levels of autonomy; for example, onboard target identification might allow downlink of target data versus complete images.

5.3 Summary of Sensor Concepts

The picture which emerges from these concepts is of a feasible, affordable approach to greatly enhanced information gathering in the battlespace through a combination of advances in individual sensor technologies and, especially, cooperative sensor operations. In general, the concepts described deal with "difficult" targets, that is, those which are hard to detect, locate, track, and classify because they are inherently obscure, embedded in clutter and interference, or protected by CCD. Specifically:

- Sensors which endure over the area of interest and build time histories of enemy activity patterns are frequently invaluable in building situational awareness and allowing focused use of sensors to deal with difficult targets. In many cases, a combination of survivable UAVs and lightweight satellites can be employed, tailored to the nature, extent, and duration of a given operational scenario.

- The key to many sensor challenges lies in higher levels of dimensionality in the signature space, achieved by fusing the outputs of EO and RF sensors in multiple spectral bands plus, in many cases, ESM intercepts, ground sensors, and other specialized devices. This is both more effective and more affordable than attempts to build single sensors with the unaided ability to prosecute difficult targets.

- In a number of important scenarios, the ability to "saturate" enemy territory with large numbers of individually inexpensive sensors, especially UGS which are emplaced by aircraft and report data through aerial relays, offer a much better, and sometimes the only, approach to the required information gathering. This is truly revolutionary when compared to the historical view of surveillance sensors as few in number and high in performance and cost.

In every case we have examined, success in providing information from sensors to warfighters is greatly enhanced by an overall architecture that defines the functions, interfaces, and operating modes of the overall information gathering structure. Such a sensor architecture is properly seen as a major segment of the overall information architecture.

6.0 Sensor Technology

6.1 Introduction and Technology Overview

This section reviews the sensor technology areas that we feel will be crucial for the Air Force in the coming decades. We focus on areas where we expect substantial change from current Air Force system practice; areas where we expect evolutionary improvements are discussed more briefly when they are discussed at all. We discuss the current status of the technologies, what developments we can expect from commercial efforts, and what the Air Force should do to assure that its needs will be met.

There are two sources for the technology areas we consider. One is the technology needed for the sensor system concepts presented in Section 5 or mentioned in Section 4. A summary is presented in Table 6-1. There are several themes that emerge from the table. One is the importance of small sensors for a variety of phenomenologies. This is for two reasons: to fit the sensors on UAVs or small (low cost) satellites that can provide continual coverage and to allow sensors that must be close to the regions being investigated to be implanted in a small covert, package. Section 6.2.1 discusses technology for MEMS and Section 6.2.7 discusses miniature sensors for detecting chemical and biological warfare agents. One feature that these sensors have in common is the use of fabrication techniques derived from the microelectronics industry and on chip placement. This offers the likelihood of low cost and the ability to integrate easily into digital signal processing systems. Section 6.2.6 discusses sensor concepts and technology for implanting the sensors and communicating with them in a covert fashion. Section 6.2.10 discusses the related idea of implanting tags, which can be detected remotely to enable the Air Force to track key targets.

There are also needs for improvements in the RF and EO sensors that have traditionally been the core of the Air Forces sensory capability. These components are discussed in Sections 6.2.2 and 6.2.3. Many of the technologies discussed in these sections concern apertures for these sensors. These apertures are frequently expensive and difficult to manufacture; requirements will get stiffer as more functionality must be packed onto smaller platforms and as signature reduction constrains designs. The aperture technologies we discuss are ways to meet these challenges in an affordable way.

The sensors described in these sections discuss the basic sensor technologies. The need for rapidly sorting through the data generated by the sensor to find targets, or at least regions, of interest forms another major theme. This is a key problem today. We already generate more imagery than can be analyzed by human interpreters. The proposals to increase the coverage of sensors will exacerbate this problem. There are two general techniques that can aid the target identification process. One approach utilizes image processing techniques to do the ID; this is discussed in Section 6.2.5 for the particular case of military vehicles including mobile missile launchers. The other approach is to add other dimensions to the data, like multiple spectral bands or vibration. This is discussed in Section 6.2.8. A fundamental shortcoming in this area is the lack of global understanding of the recognition processes. This comes both from the lack of a fundamental theory and from the lack of experience with practical military systems. The Air Force should field systems that are partial solutions to current problems to gain experience in

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the use of ATR systems, and should pursue a focused research effort to develop the fundamental theory, parallel to detection and estimation theory. This will enable the system designer, for example, to trade among different phenomenologies and resolutions. The provision of historical context also improves our ability to exploit data. The technology for doing this is discussed in the Information Application Panel Volume.

The other source for important technology is related to areas where commercial advances will offer opportunities for the Air Force either to do something that cannot be done now, or to reduce the cost of things that are done now. The principal source of commercial advances is the microelectronics industry. Many of the technology opportunities are the technologies identified in Table 6-1. One important additional area is to exploit the rapid advances in computer speed. This enables one to substitute processing for expensive sensor components. Several examples of this are described in Section 6.2.4. An example of an important future sensor concept that illustrates this opportunity is "relaxed-optical-tolerance imaging." In the next several decades, the Air Force will have an increased need for fine resolution optical imaging of targets and scenes on a global basis. Acquiring such imagery on demand for any place on the globe will be challenging, but essential, given the increasing mobility of enemy threats and terrorists, and the rapid pace with which events can unfold. The need for these capabilities implies the need for a very large number of space-based optical platforms with each having a large aperture to provide fine resolution. Using current technology, a space-based optical system with a large aperture would be very heavy to insure structural integrity and rigidity. It would also be expensive and cumbersome to fabricate and deploy. A solution to the current technology shortfall is to relax optical tolerances (thereby reducing weight) on the primary mirror and recover the loss with post detection processing. For example, the primary collector could be a non-rigid (floppy) monolithic or segmented or sparse device involving a very thin mylar surface stretched over skeleton structure. The large aberrations associated with this system would then be overcome with post-detection processing involving algorithms such as *phase-diverse speckle imaging* or *multiframe blind deconvolution*. These algorithms all involve a large number of computations that require on the order of tera-operations for a single million pixel image. The use of new algorithms and advancements in computer technology will allow the development of more affordable and improved imaging systems such as this.

Another area where commercial technology offers the Air Force significant opportunity for increased affordability is in the area of inertial sensing and geolocation. Micromachined inertial sensors and small GPS receivers offer significant affordability improvements to the Air Force. This is discussed in Section 6.2.9.

In addition to the sensor technologies discussed in Section 6.2, Table 6-1 identifies other technology needed for the sensor concepts we identified. Many of these are addressed by other panels of the *New World Vistas* study.

Table 6-1. Summary of Sensor Systems and Sensor Technology

Sensor System	Sensor Concept	Sensor Technology	Other Technology
Target Reporter UAV	ESM	Rapid data exploitation/ target recognition	Information distribution Long duration platform
	SAR	Lightweight antennas, multifrequency apertures Rapid data exploitation/target recognition	
	MTI	Adaptive high power multichannel arrays Higher resolution receivers SAR based moving target imaging	High performance computer Improved sensor cross-cueing Improved high bandwidth comm
	UGS	Small sensors, covert communications	UGS delivery
Integrated Array of Distributed Microsensors	Numerous sensors	Microsensors Low power covert datalinks	Batteries Information distribution Mobile micromachine platforms
Underground Target Surveillance	Remote spectroscopic sensor (DIAL, Passive)	On chip tunable filter Automated analysis	
	Seismic/RF tomography	Small seismic sensors HF aperture Covert communications Signal processing	Implantation batteries
	SPOT SAR	Rapid data exploitation	Information distribution
	UGS Array	Microsensors: Chem/Bio, ESM, optics, acoustics	Small mobile platforms
	TAGS	Covert communications	Implantation
All condition concealed target	Wide area surveillance	Lightweight RF aperture High bandwidth	Platforms
	CCD Penetrating radar	HF components, aperture, rapid data exploitation	Information distribution
	ESM/SIGINT	RDE/ATR	
	Imaging EO	Rapid data exploitation/ATR Advanced focal planes	
Weather Surveillance	Passive IR	FPAs (Wide band, multispectral)	Meteorology
	Passive microsensor	Wideband (1-200 Ghz) aperture, synthetic aperture radiometry	
	LIDAR	Laser sources/packaging	
	Radar	20-100 GHz apertures	
	Modular integrated multi-EO	Optical phased array wideband fiberoptics IR clutter processor Advanced FPAs	
	Enhanced Active/Passive spectral sensing	Advanced Focal Planes On-chip tunable filters Tunable Lasers	
	Supply chain tagging	Tagging Materials	Implantation
	Multispectral EO/IR for wide area	Very high spectral response Uniformity in FPAs	Tunable lasers Tunable filters
	Low cost 3-D laser radars	APD arrays Modulated corner cube	
	High resolution SAR	A/D, modules, apertures	
Boost Phase Intercept	High power aperture UHF airborne radar	Lightweight aperture TR modules	
	Optical tracker for ABL	Advanced focal planes	
	Continuous surveillance SAR	TR modules	Launch costs, solar panels, information distribution
	Seismic radar	Miniature seismic sensor	
	FOPEN radar	Low frequency aperture TR modules	
	Multispectral imaging	Multispectral arrays (uncooled)	
	Building implantable sensors	Miniature seismic acoustic, RF sensors	Implantation
Self-diagnosing Aircraft	Engine monitors	Small spectroscopes Small acoustic sensors	
	Structural monitors	Acoustic transducers (Eddy current)	Propagation models
	RF/EO analog electronic	Calibration patterns	Machine reasoning
	BIT/FIT		
	Engine boresiting robots	Machine vision Miniature EO comps	Miniature robotic locomotion

6.2 Technology Areas

6.2.1 MEMS and Nanofabrication

Following in the footsteps of the microelectronics revolution, the emerging MEMS technologies offer the next step in on-chip integration. By integrating mechanical, optical, and other functions along with microelectronics, MEMS enables the next phase of system miniaturization in which transducers, actuators, control electronics and signal processing can all reside on a single chip. MEMS are fabricated using similar lithography and etching techniques developed for the micro-electronics industry, modified to create mechanical and optical structures as well as electronic devices. To date, this new technology has been pioneered in silicon, where direction-specific etches are already well known. Eventual development in other materials systems will permit integration of more diverse components and functionality's. The full range of military applications of this emerging technology is hard to predict, but will include such diverse areas as microsensors for in-situ surveillance and reconnaissance, embedded sensors for autonomous vehicle and aircraft systems, microactuators for adaptive and precision alignment of imaging systems, and microjets for turbulence control over airframes.

Micromachined Transducers

Physical sensors are likely to be some of the first applications of emerging MEMS technologies. New transducer technologies, such as those based on electronic tunneling, micromachined balances and capacitive plates, and chemically induced electronic and acoustic property changes, offer significant performance advantages in terms of signal/noise versus sensor size. In many cases, they also offer enhanced dynamic range, and are considerably more robust than their conventional counterparts. Micromechanical-transducer-based sensors also offer the potential of extended ranges of operating conditions, including wide thermal swings, high radiation environments, and high and low pressures. Thus they are appropriate for a wide range of environments. Finally, since MEMS, like micro-electronics, is based on a mass-producible fabrication technology, the price for such systems can ultimately be very low.

Tunnel sensors are based on the quantum mechanical tunneling current that flows between a tip placed within a few Å of a surface so that the electronic wavefunctions overlap significantly. Since the wavefunction tails fall off exponentially over distances on the scale of Å, this current is extremely sensitive to the relative position of the two surfaces—changes on the order of 1/100 Å can be detected. This transducer can be used as a sensor for any phenomenon that can be transformed into a change in relative displacement. To date, accelerometers, hydrophones, magnetometers, non-contact current sensors, and broadband, uncooled infrared detectors have been demonstrated.

Microactuators

Microlithography can be used to fabricate mechanical actuators that will be the basis for miniaturized guidance and control systems for autonomous vehicles and for the precision control of the position, pointing and shape of optical surfaces. For example, gyros with drift below 1°/hr are envisioned that can be used for autonomous satellite navigation. The need to lower the mass of future space systems can be met with deployable optics, but only in combination with microtechnologies able to maintain a precision surface conformation to retain the desired imaging capability.

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Micro Optics

As the resolution achievable with nanolithography attains the scale of optical wavelengths, this area is also having a major impact on optics and optical systems. The fabrication of surfaces with submicron feature sizes enables controlled, efficient diffraction of light. Applications include holographic optical elements such as on-chip focusing optics, gratings for diode lasers and wavelength-division multiplexing, and nm-scale Ronchi rulings for high resolution interferometry. On-chip optics is important for emerging smart-focal-plane imagers, in which part of the detector surface is sacrificed for signal processing functions. By focusing the light only on the active portion of the pixels, the sacrificed quantum efficiency can be returned. On-chip optics is also a fundamental element of optical imager processing. Lithography on the nm scale is also required for the fabrication of high-frequency receiver components, phased-array antennas and chip-level photonic devices. For example, single-frequency diode lasers offer new approaches for active spectroscopy valuable in determining the nature of air-carried chemical species, or to profile atmospheric winds.

Microchemical Sensors

Microchemical sensors can be fabricated using a variety of chemically sensitive surface effects, such as changes in SAW frequencies (devices) and changes in the resistivity detected in chemical field effect transistors (chem-FETs). These devices can discriminate between different chemicals, especially when deployed in arrays with a range of device parameters. A variety of fiber-optic approaches are also possible including the sensing of degradation of thin film reflectors at the end of the fibers, and effects on internal reflection from the fiber surface and internal reflecting gratings. By the turn of the century, it may be possible to manufacture an entire mass spectrometer, including sample manipulation, vacuum electronics, electrostatic imaging, and species identification intelligence, on a single chip. A variety of thermodynamic parameters such as pressure, temperature, and vector wind velocity can also be measured with these on-chip technologies.

Applications

These types of miniature sensors enable new scenarios in surveillance and reconnaissance. Producible in very large numbers and requiring very little power, these sensors are ideal for "spraying" or flying in mini UAVs over potentially hostile areas to detect signature chemical species, to return visible (or other wavelength range) images of the area, and to detect activity above ground, underground or underwater. The deployment of many sensors is, in itself, an excellent strategy for survivability. Combining on-chip sensors, controllers, signal processing and transmitters results in a complete system for autonomous detection and warning. Fully autonomous satellite stationkeeping and constellation configuration maintenance are also feasible with on-chip gyros, accelerometers and GPS receivers.

Development Strategy

MEMS is advancing rapidly in the commercial sector, and many of the desired functionalities for military applications may be developed by industry. However, the USAF needs to monitor the development and be prepared to support the adaptation to military-unique applications. In many cases, the need for on-demand global knowledge, and the desire to remove

military personnel from harm's way, drives performance specs in sensitivity, resolution and signature discrimination well beyond those being addressed by the commercial market.

6.2.2 EO Components

Introduction

As EO sensors play an ever expanding and increasingly important role in the Air Force's missions, the development of advanced electro-optics components becomes increasingly critical as the key enabler for the systems. Indeed, the development of new sensor capabilities is often paced by the availability of EO components, and, for foreseeable advanced systems, this is even more likely to be the case. The importance is especially apparent when it is realized that the role of EO components has expanded from primarily a sensing/detecting function to include using EO for target designation, communication, control, probing, and potentially signal processing. This section examines the status and future for Focal Plane Arrays, Laser Radars and Filters, Space Fed Optical Phased Array, T/R Module Based Optical Phased Array and On-Chip Tunable Sources.

Advances in focal plane arrays over the last few years have been dramatic. Large format (> 4,000,000 pixels), high density silicon-based visible sensors are readily available. Platinum silicide (PtSi), indium antimonide (InSb), and mercury cadmium telluride (HgCdTe) arrays for the 2 to 5 micron spectral region are becoming available in arrays sized up to 1024 by 1024 pixels. HgCdTe arrays of up to 480 by 640 pixels for 8 to 12 micron spectral region are being demonstrated in laboratories. Uncooled 240 by 320 arrays for 8 to 12 micron sensing are commercially available. Major technical challenges of HgCdTe material uniformity, size (> 24 cm^2) and uniformity have largely been met. Advances in read out integrated circuit (ROIC) technology have increased the frame rate, noise and MTF performance of focal planes. Efforts continue to shrink pixel size, to increase sensitivity of IR arrays at stressing signal levels, and to improve the producibility and reduce costs. In addition 128 by 128 HgCdTe arrays sensitive to two spectral bands simultaneously have been demonstrated in laboratories. These developments are supporting Air Force FLIRs, missile seekers, IRST, Threat Warning and Surveillance requirements.

Future developments in Focal Plane Arrays should focus on large format (> 2,000,000 pixels), high density (< 20 microns square) arrays for enhancing performance in FLIR sensitivity, enabling strap-down seekers, increasing coverage for IRST and Threat Warning and enabling multifunction, common aperture EO systems. Multispectral FPAs which collect simultaneous images from two or more bands will support the trend to better target identification, clutter rejection, or background suppression that is desirable for smart and/or autonomous weapons systems. Monolithic implementations for uncooled sensors with improved sensitivity attained by the use of thin film sensing material and improved thermal isolation with smaller cells can expand the effectiveness for Air Force missions. Quantum well and strained layer superlattice arrays may offer advantages in some niche applications and considerable development is required for these technologies to become competitive with existing technologies. The potential payoff versus current technologies should be seriously assessed. ROIC technology should concentrate on high speed readout rates (> 500 frames per second), increased charge storage density, increased cell density (i.e., tighter design rules), reduced noise and improved linearity. Techniques for

uniformity correction of high sensitivity FPAs which will decrease the output data rate (perhaps by fovial processing or windowing), reduce the dynamic range, maintain the signal correctability, and possibly implement on-chip ADC. Combinations of these functions or others which will accommodate improved system effectiveness may lead to "smart FPAs." The requirement for multimode systems should be assessed and a determination made whether to develop an IR/mmW sensitive array. FPA developments will enable more sophisticated FC, NAV, and weapons systems over the next 10 years.

Laser Radar has applications to multiple Air Force missions. Among these are target recognition, three-dimensional imaging, wind sensing, gas cloud sensing, wire detection, some cloud penetration capability, terrain following/terrain avoidance/obstacle avoidance and FC support. Significant advantages are offered by the capability to control the probing source and by using its interaction with various objects to gain discrimination information. However, increased power lasers are required to approach the capabilities of microwave radar. Wavelength tunable lasers could offer advantages in target recognition.

Future developments should concentrate on low repetition rate laser radars for designators, and target ID wavelength tunability needs to be developed at the proper power levels to enhance performance and target discrimination. The development of full three-dimensional imaging laser radar seekers could improve all-weather precision strike for high performance missiles.

A major breakthrough would be the implementation of the "conformal," multimission optical system that would perform A/A and A/G target ID and detection, laser communication, missile warning, and IR missile countermeasures. Such a system could be implemented using a space fed optical phased array in each aperture module. Future versions of a multifunction concept could use a T/R module based phased array concept. This project has many very challenging developments because of the requirement to fabricate components and modules which operate at optical wavelength dimensions instead of microwave dimensions. The development of such a system would take many years but could potentially provide revolutionary capabilities in an affordable subsystem. In order to possibly achieve this capability, a number of 6.1 and 6.2 efforts are proposed for the near term.

On-Chip Tunable Sources and Filters are of great importance to multiprocessor interconnect, phased-array radar, multisensor fusion and information distribution applications. Miniaturized high power tunable lasers are currently limited by the availability of intracavity tuning and high power optical pumps. Semiconductor diode lasers can ultimately provide the pump, and several tuning techniques are under investigation but have not reached the maturity level needed. Development of these technologies is key to increase data transfer, provide self-healing control networks, increase computational capability, and code signals for security. This area can leverage heavily off of commercial developments, but the Air Force must invest to meet RF signal generation, high power generation and military temperature requirements.

Wavelength tunable active and passive EO devices are critical to the exploitation of the wavelength "dimension." Increasing the dimensionality of our sensing space is one of the more promising new sensor concepts, as discussed in Section 6.2.8.

It is recommended that the Air Force structure a program in this area to align requirements with commercial developments and to address requirements peculiar to military applications.

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Additional efforts in control system developments for multichannel processors and packaging are proposed. Continued 6.1 efforts to develop new materials for compact lasers must be pursued.

Electro-optics components will continue to be integral to Air Force systems and key developments are needed to advance the capabilities of future systems.

6.2.2.1 Focal Plane Arrays

Summary of Current Focal Plane Array Performance

Current focal plane array technology includes numerous high spatial resolution off-the-shelf devices for the UV through LWIR wavelength range. In general, visible device technology is more mature than that found in the IR. This is related to the fact that near-optimal visible-light and near-IR detectors can be fabricated from silicon, using many of the methods already developed for conventional integrated circuit manufacturing. The optical detector array and readout circuitry are usually fabricated all in one piece, resulting in a "monolithic" image sensor. UV sensitive devices are typically made by coating a visible-light FPA with a fluorescent coating. In the visible, state-of-the-art focal plane arrays will soon be available with as many as 25 million pixels, arranged in 5000 by 5000 format on 12-micron centers; pixel sizes down to 6.8 microns can be obtained in certain other devices.

In the IR, many different detector materials have been developed to serve different wavelength ranges and mission requirements. Each material requires different exotic processing techniques to produce a detector array, and most often these arrays must be attached to separate silicon readout circuits using special assembly techniques that result in a sandwich or "hybrid" image sensor. The need to separately develop these specialized material processing and assembly techniques and the lack of a commercially driven technology base has resulted in slower maturation of IR devices.

In the SWIR and MWIR (1 to 5 microns wavelength), state-of-the-art devices include monolithic arrays of PtSi, and hybrid arrays of InSb and HgCdTe. Platinum silicide arrays are now commercially available with 640 by 480 elements, arranged on 24-micron centers; devices with up to 1040 by 1040 elements on 17-micron centers have also be reported. Indium antimonide arrays with over 1 million elements, in a 1024 by 1024 format on 27-micron centers, and HgCdTe arrays, with 1024 by 1024 pixels, are now undergoing laboratory testing.

In the LWIR (8 to 12 microns) and beyond, detector types include long-wave mercury cadmium telluride and extrinsic silicon. Mercury cadmium telluride devices are available in 256 by 256 format on approximately 40-micron centers, with up to 640 by 480 devices under research. Extrinsic silicon devices that respond in the wavelength range 2 to 28 microns will soon be available in a 320 by 240 format, on 50-micron centers.

Incremental Improvement of Basic FPA Performance

Given the current state of the art in focal plane arrays, let us now consider the directions that new focal plane array developments are taking. One may classify FPA properties and their improvements in many ways. In our approach, we will first discuss FPA properties that directly influence the conversion of light to an electrical signal. Improvements that enhance system operational performance will be addressed in the next section.

The most basic function of a focal plane array is to sample the optical image that is focused on it. To perform ideally, the focal plane array must convert all light put on it into an electrical signal, and it must pass this signal to the outside world with no added noise. This aspect of its operation is broadly referred to as its sensitivity. Additionally, the focal plane array output from each detector must minimize coupling of signals between neighboring pixels. This aspect of performance is usually summarized by the FPA's modulation transfer function (MTF).

The sensitivity of any focal plane array is related to several properties—detector quantum efficiency, including optical transmittances, detector dark current, readout noise, and detector fill factor. In the visible, incremental sensitivity improvements continue to be made through improvements in each of these areas. Special techniques include the use of back-side illumination, special optical coatings, and tin-oxide gate structures to optimize quantum efficiency, MPP operation to lessen dark current, and buried-channel readout amplifiers to lessen readout noise. In the infrared, key detector materials are undergoing constant refinement to improve sensitivity. Quantum efficiency gains have been secured in PtSi through refinement of the wafer preparation and platinum deposition processes, and the addition of Fabry-Perot microstructures to the detectors. Notable advances have been made in other materials to reduce detector 1/f noise and dark currents through improved materials purity and processing techniques. Microscopic lens arrays to increase effective detector fill factor have also been discussed.

Modulation transfer function of a focal plane array is influenced both by the detector array electro-optical properties and the electronic readout circuit. To optimize MTF, each specific FPA design must control the optical crosstalk present at the detector and the electrical crosstalk introduced by the electronic readout structure. Current designs in the visible control MTF by maintaining excellent charge-transfer efficiency and by using tightly-confined collecting wells at the point where the optical-to-electrical conversion process takes place. MTF in hybrid IR FPA designs can be dominated by electrical crosstalk occurring in the CCD readout electronics, but has been overcome by the use of CMOS readouts. In these designs, some additional improvements have occurred through the use of higher-bandwidth readout electronics. Optical crosstalk in current IR FPAs is rather poor—as high as 5 percent between nearest neighbors for backside illuminated hybrids, but improves to ≤1 percent for the frontside illuminated hybrids.

Incremental Improvement of FPA Operational Performance

When one considers the inter-relationship between the FPA and overall system operational performance, it becomes obvious that a number of FPA properties (beyond those that define its sensitivity and MTF) must be taken into account. These properties include the pixel dimensions, spacing, and overall number, readout rate, uniformity and linearity of response, dynamic range, operating temperature and cooling method, price, and defect numbers and type. In this section, we will comment on several examples of the incremental technology gains being made in these aspects of FPA design and performance.

One of the most important themes in this area of focal plane development has had to do with the layout of the FPA itself. The goal has been to produce larger arrays of pixels with smaller interpixel spacing, while maintaining large active areas and low defect rates. The achievement of these goals has been hampered in visible-device production by microlithography line-width limits, silicon wafer size limits, and cleanliness standards. In IR FPA development, similar technological limits exist for the silicon readout circuits. Additional technology limits in

the IR have to do with large-scale growth of IR detector materials, and differential thermal expansion limits that apply to the hybrid structures employed here. Incremental improvement in HgCdTe material size (> 24 cm²), microcircuit fabrication techniques, moving to larger wafer fabrication sizes, and using interconnect (vs. bump bond) and special assembly techniques in the IR devices have largely overcome the limits on total pixel count.

Another area of incremental improvement has been in the area of readout rate. Here, higher overall readout rates are being secured through the use of special device architectures that feature multiple readout lines, each operating near the speed limit that earlier devices have employed on single readout lines. Another strategy in visible-light FPAs involves splitting the image field into two parts and then reading each of these out over multiple output taps. Internal pipelining has been recently employed in IR devices to overcome slow internal settling times, and hence an increase in readout rate has been obtained.

Dynamic range improvements in the MWIR have been secured in recent designs through use of specialized high-voltage VLSI processing, high capacitance density structures, and special integrating circuits for the readout structures, thus permitting very long integration times and large full-well signals.

In addition to the price advantages gained with better microcircuit fabrication yields, there has been significant interest in raising the operating temperature of IR detectors. The costs associated with cooling IR detector arrays are severe, and raising operating temperature would do much to reduce IR detector purchase and operating costs. A notable achievement in this area has been the recent release of a MWIR HgCdTe FPA that will operate with a simple thermoelectric cooler. This makes it a clear choice over LN2-cooled InSb arrays in applications where a shorter cutoff wavelength is acceptable. In addition, advances in linear drive closed cycle cryocoolers have increased reliability and reduced costs.

Finally, there has also been much interest, at least at a concept level, in on-focal-plane processing, sometimes referred to as a "smart pixel approach." Smart pixel concepts include on-chip ADC, adaptive response NUC, morphological signal processing, thresholding of detector outputs, and logarithmic signal compression. Although these approaches are attractive at the concept level, they will tend to add power dissipation at the FPA, and must be evaluated in the context of an overall cooling budget for the detector assembly. Related to these concepts MEMS that may eventually fuse conventional image-sensing operations with other types of sensing capability.

"Break-through" Focal Plane Array Technology

Certain problems in the fabrication of FPAs have not yielded to incremental engineering solutions. This has prompted new research, aimed at creating entirely new classes of FPA devices. Perhaps the most important problems of this type have been in infrared FPAs and have to do with the unreasonably high costs associated with making defect-free devices and the unreasonably high costs associated with cooling.

In answer to the cooling issue, two new technologies have been created—micro-machined silicon bolometer arrays, and ferroelectric FPAs. Technology demonstration projects have shown that reasonable sensitivity and MTF can be achieved with both technologies in large image formats. These devices operate in the LWIR, with complete camera costs of under $10,000. The

FPA operates near room temperature, in contrast to typical LWIR detectors that operate at liquid nitrogen temperature and below (Figure 6-1). These FPAs appear to have tremendous potential for low-sensitivity, volume production applications. Although available signature strengths are weaker in the MWIR, it seems likely that at least some class of Air Force problems here might benefit from uncooled FPAs, particularly for threatwarning applications. In HgCdTe, array structures that sense MWIR and LWIR images simultaneously in spatially congruent arrays have been demonstrated in laboratories up to 128 by 128 arrays with sensitivity and uniformity approaching single color devices. Advances in linear cryogenics coolers have increased the mean time between failures (MTBF) to > 4000 hours and greatly improved efficiency and size for tactical applications. These techniques could be applied to strategic needs with efforts focused on increasing lifetime.
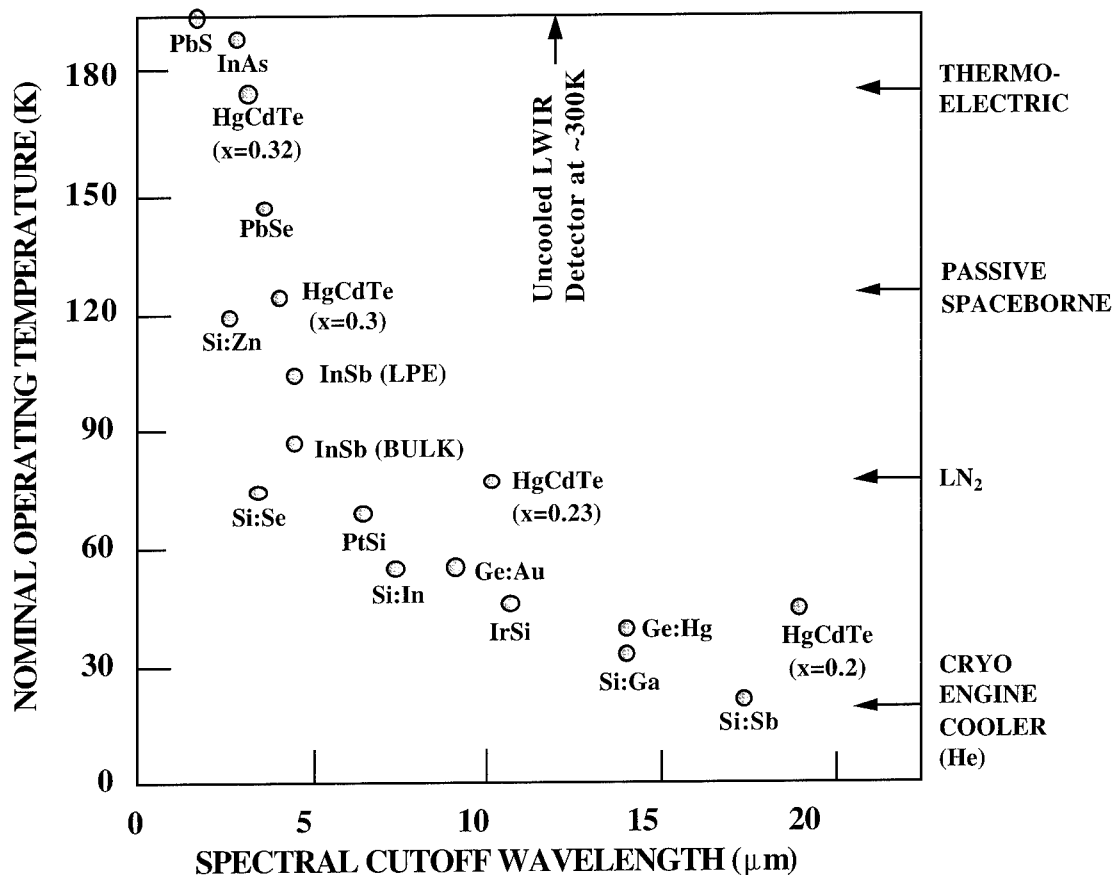
Figure 6-1. Conventional Photodetector Operating Temperature Versus Wavelength

In answer to the producibility problem, another line of research has resulted in a special class of detector that is fabricated with molecular-beam epitaxy (MBE). These detectors operate on quantum-confinement principles, with modest QE in the LWIR. Although cooling requirements are more severe than existing LWIR detectors, this approach is thought to offer very good detector

uniformity and yield, even at very large array sizes. This yield enhancement, relative to conventional LWIR materials, may provide substantial affordability gains. This approach also offers the possibility of electronic bandwidth control, where a variable electrical bias will be used to control the center wavelength of the detector's optical response (Figure 6-2). Alternatively, the center wavelength for each pixel may be set individually at the time the device is manufactured. These possibilities suggest that specialized FPAs could be constructed to provide multispectral image output.
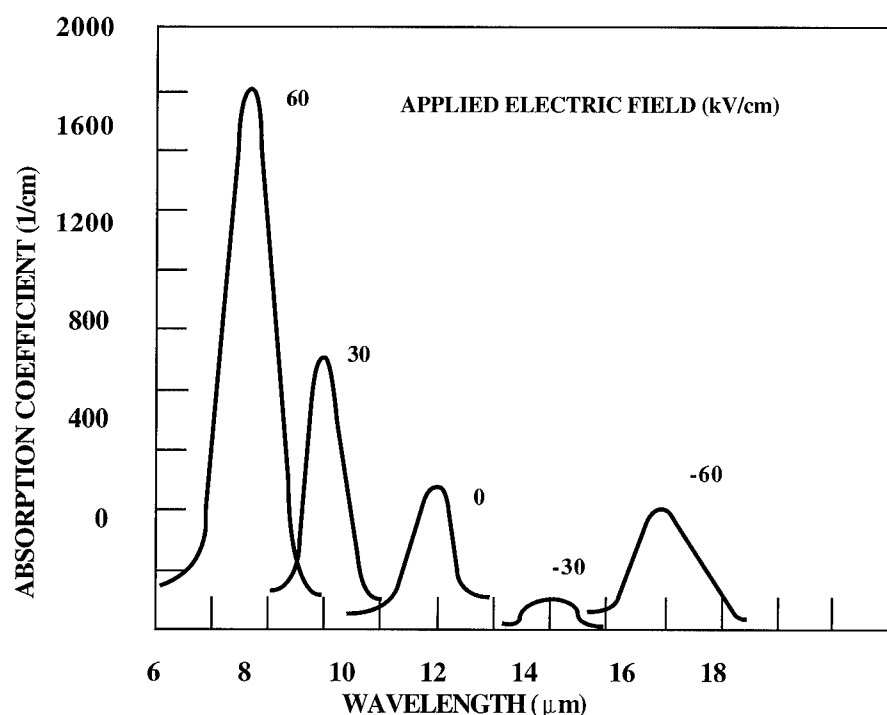
Figure 6-2. Multicolor Quantum Well Infrared Photodetectors. Center wavelength can be set by means of applied electrical bias.

FPA Technology Trends

Perhaps the most frequently used measures of FPA technology growth are the overall device pixel count, and the inter-pixel spacing, or pitch. Secondary trend metrics include readout speed, unit price, and various sensitivity and MTF measures discussed in prior sections.

For example, Figure 6-3 illustrates the growth in overall array size for silicide infrared FPAs. This chart shows that the rate of growth in these arrays is identical to that of dynamic ram memory chips, with a lag time of 5.5 years. Similar growth has been seen for other FPA types. Recently, a 256 Mbit memory chip development project was announced by IBM, Siemens and Toshiba. If this effort is successful during the next several years, it is fair to conclude that the trend in memory growth has not "rolled over" yet, and that further increases in FPA size are possible.
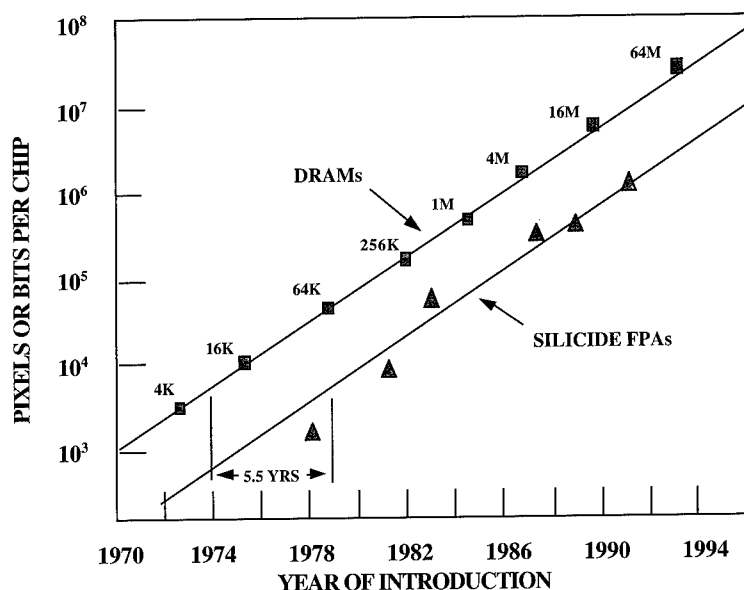
Figure 6-3. Silicide Infrared Arrays—A Comparison With Silicon Dynamic Ram Memory Devices (DRAMS)

In Figure 6-4, the trend in silicide pixel size is shown as a function of time. It is clear that the need to decrease cell size as well as the technology to do so was present up to about 1987, when active area sizes stagnated at around 520 square micrometers. At this time, this active area corresponded to a 26 by 20 micron pixel, in a 512 by 512 MWIR device. Note that the state of the art four years later had only dropped to 290 square micrometers, corresponding to a 17 by 17 micron pixel in a 1040 by 1040 device.
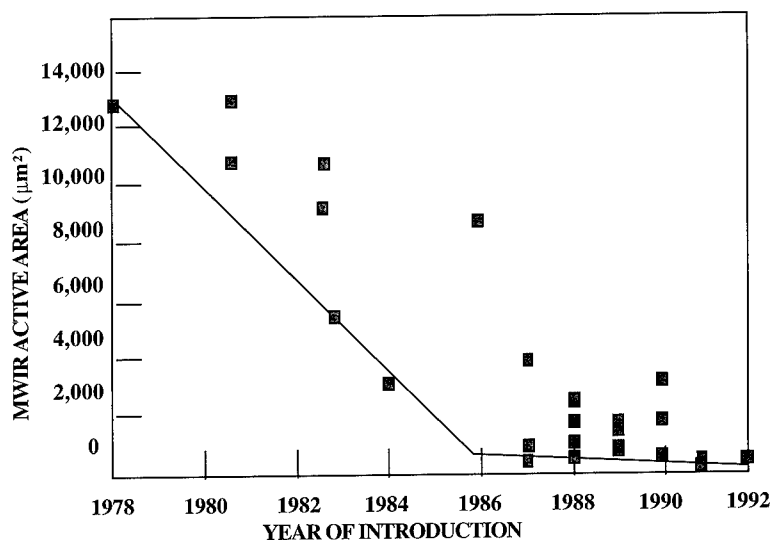
Figure 6-4. Trend in Active Area for Silicide Infrared Pixels

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It is thought that this stagnation may be related to the fact that silicide FPAs have reached a size where they can map pixel-for-pixel from the sensor to a typical video monitor. Devices of this size can be fabricated with rather large (and easy to make) pixel dimensions, thus there has not been a compelling reason to reduce pixel size further. In addition, pixel sizes are approaching the diffraction limit for tactical systems.

If one considers other applications, however, it seems fairly obvious that these and other current FPAs are not well matched to the optical systems that feed them. This leaves open the possibility of aliasing, in addition to under-utilization of the spatial frequency content that can be delivered by current optical designs.

Table 6-2 illustrates this concept. For the visible, MWIR, and LWIR bands the table shows representative values for the Nyquist sampling interval demanded by various optical systems. Also shown is the state of the art in FPA pitch. Clearly, current FPA designs have not advanced to the point where they make full use of their input images. This type of FPA development is complicated by other factors besides those having to do with the layout of the device itself—the charge storage capacity for each pixel goes down with the active area, which reduces the dynamic range of the FPA.

Table 6-2. Comparison of Optical Systems and Focal Plane Array Pixel Pitch

Wavelength (microns)	Optical System F/#	Incoherent Cutoff Frequency (cy/mm)	Required Nyquist Sampling Interval (microns)	Current Device Pitch (microns)
Visible 0.5	2 8	1000 250	0.5 2.0	6.8
MWIR 4.0	2 8	125 31	4.0 16.0	17.0
LWIR 10.0	2 8	50 12	10.0 40.0	40.0

Future Air Force systems, such as high resolution reconnaissance sensors, might greatly benefit from reductions in FPA pixel size. Perhaps commercial needs will push FPA development in this direction as well.

Uniformity correction becomes more critical for all FPA approaches as the sensitivity limits are improved. The trend is to develop scene-based algorithms and increase the FPA correctibility. This is a critical effort to realize the full potential of staring arrays.

Application of Focal Plane Arrays to Key Air Force Missions

The following sub-sections summarize a few examples of specific electro-optical sensor functions that are needed to serve various Air Force missions, emphasizing why FPA technology is important and what benefits it produces.

Bomb Damage Assessment

The challenge here is not only one of sensor design but also phenomenology. How do you know when a visually damaged target is no longer able to contribute to the enemy war effort? To

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date, Air Force efforts involve daytime visible and nighttime imagery of the bombed target from a variety of sensors and airborne platforms. With the advent of visible and infrared focal plane technology, line scanners and cameras were developed with spatial resolution nearly comparable to that obtained with film. Because bomb damage assessment requires detailed imagery of a bombed target, focal plane advances in smaller detectors, longer focal plane arrays, and higher sensitivity through TDI have been needed and have been forthcoming.

Bomb, Missile, and Projectile Guidance

The objective is to accurately put bombs on desired targets and destroy them. The challenge lies in guiding the munition to a target that is difficult to detect in the first place or that is amid civilian structures, whose destruction is politically unacceptable. These weapons use a variety of sensors to seek out targets. There are versions that use visible light television cameras, infrared scanning sensors, laser designators, and radar imagers and more recently staring arrays.

Situational Awareness

An important mission requirement of Air Force pilots is situational awareness—to know the location, type, speed, and intention of every aircraft and missile within fifty miles of their aircraft. To accomplish this goal, historically two types of sensors have been developed—IRST sensors and MWRs. The IRST sensor strives for long-range detection in as large a forward cone, or field of regard, as possible in front of the sensor aircraft. The MWR concentrates on surface-to-air missile launches in the hemisphere below the sensor aircraft and also to some extent aircraft attacking from the rear with A/A missiles. For both sensor types, the challenge is achieving the desired sensitivity and bandwidth from the focal plane arrays and expanding the capabilities to multiple spectral regions to aid in target discrimination.

IRST Sensors

Initial IRST sensors used MWIR InSb focal plane arrays to detect hot engine parts and the hot exhaust plumes extending out behind the target aircraft's engine. Improving HgCdTe focal plane arrays for the LWIR suggested longer detection ranges than were possible in the MWIR, especially when the target aircraft was not flying in afterburner or was approaching nearly directly nose-on so that much of its engine hot parts and plume are obscured. The IRST sensor deployed on the Navy's F-14 uses a linear 256 element HgCdTe array. The IRST sensor planned for the Air Force's F-22 would have used a 480 element long by 4 TDI focal plane array of HgCdTe detectors. The use of TDI provides improved sensitivity and hence increased detection range and/or faster scans of the field of regard and/or larger possible fields of regard. Another focal plane array improvement is the availability of smaller detectors, which can be used to increase target signal-to-noise and to make more efficient signal processing techniques that extract targets from background clutter. Ideally, the target should just fill the instantaneous FOV. Failing that, the instantaneous FOV containing the target should contain as little background as possible.

Missile Warning Receiver (MWR)

MWR sensors use one or more bands in the MWIR to detect the hot exhaust plume during the launch of a surface-to-air missile and to track it during its powered flight. Earlier MWR

sensors such as the AN/AAR-44 deployed on special operations C-130 aircraft used linear InSb focal plane arrays to scan the scene. With the development of two-dimensional InSb focal plane arrays in recent years, staring MWR sensors have been designed. The missile launch detection (MLD) system for the F-22 uses 128 by 128 detector arrays in staring mode. Such staring sensors can have much more sensitivity and/or image update times over their scanning counterparts. One problem posed to the staring sensor is how to cover the large field of regard required. The F-22 MLD system solves this problem with several staring sensors, each with its own FOV that is part of the total field of regard. Alternately, a single staring sensor could be scanned.

Identify Friend-or-Foe (IFF)

There have been several incidents of the accidental destruction of friendly forces in recent years. IFF is an important step in target characterization or classification. While much of it has been done between aircraft with coded radio beacons, the Navy F-14 has used a visible television sensor mounted in the F-14 chin pod. This sensor, the television camera set (TCS), has been upgraded to include a silicon 525 by 525 element focal plane array and provides the pilot an image of approaching aircraft from a range far beyond the visual range of the pilot.

Strategic and Theater Missile Defense

The Air Force and the Army have the joint mission of detecting hostile surface-to-surface launches of intercontinental ballistic missiles as well as shorter range missiles and accurately tracking their trajectory and warhead deployment so that the attacked facilities can be warned and the incoming missiles can be possibly successfully intercepted. Missile launches can be detected from space using one or more bands in the MWIR with a linear array of detectors scanned across as large a region of the earth as possible, limited by the altitude of the sensor and the number of elements in the array. Sensor concepts for this challenging mission usually require large staring (e.g., , 1000 by 1000) LWIR focal plane arrays of HgCdTe or extrinsic silicon (Si) detectors.

Relationship to Commercial Developments and Applications

Many commercial applications require the special properties of focal plane arrays. The next several sections touch briefly on several of the more important examples of commercial FPA use.

Film Replacement Market

Kodak, Fuji, Canon and other manufacturers now produce 35mm cameras that use a visible-light CCD at what was once the film plane. These cameras provide the benefit of instant turn-around on images, digital picture format, and reasonable low-light sensitivity. Image resolution is not equivalent to that of film yet, and purchase prices are high; one would expect that the driving issues here are the need to decrease pixel size, increase pixel number, and to reduce unit prices. It would appear that the commercial push for smaller visible pixels will allow significant leverage for Air Force projects.

Industrial Inspection and Robotics Market

Large-format cameras (large number of pixels) for industrial use are now produced by Photometrics, Ltd., Sony, and others. Key considerations in the design of these cameras are image format, linearity of photoresponse, freedom from optical overload (blooming) problems, low-light-level operation, compatibility with existing computers and factory automation equipment, and reasonable purchase price.

Astronomy and Scientific Research

Astronomy has traditionally driven the development of large visible imagers. Suppliers such as TI, Thompson-CSF, SITE, and Photometrics have served this market well. It is now the case that astronomy needs in the MWIR are also impacting leading-edge FPA development, with the SBRC Aladdin project (1024 by 1024 InSb FPA) and Rockwell 1024 by 1024 SWIR HgCdTe serving as noteworthy examples.

Entertainment Industry

The home video market has been largely responsible for the low costs that now apply to moderate size (both physical dimensions and pixel count) color CCDs. Perhaps the next trend in this area will be the emergence of low-cost HDTV sensors, first to serve the broadcast marketplace, and then high-end robotics and inspection uses. Both Phillips and Kodak now offer color HDTV CCDs in 16 by 9 format, consisting of roughly 2000 by 1000 pixels that can be read out at 30 frames per second. This rapid readout, at high resolution, will doubtless permit the creation of numerous new Air Force systems without further technology investment.

Power Distribution Maintenance, Heating and Ventilating, and Combustion Engineering

One of the first commercial applications for IR FPAs was in the electric power industry, where IR cameras are used to detect "hot joints" in power distribution equipment. Of additional note are applications in heating and ventilating, where homes and commercial buildings are surveyed for areas of excess heat loss, and similar applications in power plant maintenance and combustion engineering.

Civilian Remote Sensing Programs

Numerous programs sponsored by NASA and foreign space agencies have called for specialized devices that feature large image formats, response to unique wavebands, and the ability to withstand large radiation doses. The Air Force benefit here perhaps parallels that offered by the Astronomy and Scientific Research marketplace.

Law Enforcement and Automotive Industry

It is believed that research on automotive applications for night vision has been conducted for at least 10 years. It is clear that low cost and reliable operation, in a reasonable TV-like format, are the primary requirements for the FPAs for these systems. Manufacturability gains in uncooled FPA systems obtained in these projects will directly benefit future Air Force purchase prices. However, for increased sensitivity, additional work is required.

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Summary of Commercial Applications

Table 6-3 summarizes the key areas in which commercial activities appear to be influencing the development of FPAs.

Table 6-3. Summary of Commercial Development Activities

Commercial Application	Focal Plane Array Attribute or Metric								
	Large No. of Pixels	Small Pixels	Video Readout Rates & Higher	Multi-spectral Capability	Linearity	High Dynamic Range	Uniformity	Blooming Control	Low Cost
Film Replacement	X	X				X	X	X	X
Industrial Inspection	X				X	X	X	X	
Astronomy	X				X	X	X		
Entertainment	X		X						X
Therography			X						X
Civilian Remote Sensing	X			X	X	X	X	X	
Law Enforcement/ Auto.			X						X
Air Force Leverage	X		in visible band		X	X	X	X	in some FPA, such as PtSi & uncooled

Affordability Impact

The development of large, multispectral staring focal plane arrays will have a dramatic impact on weapon systems affordability. By utilizing an integrated multifunction sensor suite (e.g., NAV, F/C, targeting, IRST,...) future aircraft can be developed that are multimission and multirole, providing for significant life cycle cost savings during A/C volume production. In addition, an integrated multifunction sensor suite will significantly reduce the sensor life cycle costs by eliminating the need for multiple, independent sensors. Recent studies under the JAST program have shown that life cycle cost savings on the order of 6x are achievable with this approach.

The use of uncooled sensor technology dramatically reduces the cost of imaging systems through the elimination of costly ternary semiconductor detectors and their ancillary cooling systems. The broad spectral capability of the uncooled detector can also make a significant impact on total systems cost. A single, relatively low-cost detector can be utilized to cover all radiation bands of interest.

Advances in FPA performance will continue to offer efficiency improvements in several applications. One example is digital photography. The widespread use of "film replacement" CCDs in camera systems should offer the Air Force more rapid decision-making capability, lower personnel costs, and savings in material costs, in comparison to current film-based systems.

Other efficiency savings accrue from the inherently digital nature of most FPA-based systems. As conventional photographic systems are replaced by FPAs, the costs associated with operations such as document scanning, transmission, and archiving of negatives will go away entirely. Reproduction of digital images should also offer cost advantages over traditional methods.

Tremendous reliability improvements can be secured through use of FPA-based staring systems, in contrast to earlier-generation scanning imaging systems, owing mainly to their non-mechanical nature. Reliability problems in current FPA technology exist mainly in the LWIR, where it is difficult to establish long-lasting electro-mechanical bonds between detector arrays and their silicon readout structures. Recent results with via-interconnected (vs. bump-bonded) arrays at Texas Instruments (TI) indicate size limits may have been overcome. This may in part be solved through the use of uncooled FPAs in lower-sensitivity applications.

Another reliability issue for MWIR and LWIR systems has to do with the mechanical cryocoolers that are used to stabilize the FPA at its proper operating temperature. This problem may also in part be solved through the use of uncooled FPAs.

Recommended Development Plan

In general, the Air Force development plan for FPAs should be marked by a series of additional studies, accompanied by specific demonstration projects, with enough flexibility built in advance to take advantage of yet unknown FPA technology break-throughs. An overview of the recommended process is:

- Define and prioritize FPA needs, relative to an agreed-upon list of specific AF missions requirements and related, supporting capabilities.

- Analyze these FPA needs and delineate physical versus technological limits.

- Analyze technological hurdles—the steps that are thought to be needed to overcome them, costs, and payoff potential for the commercial sector.

- Establish a series of time-lines and intermediate goals for the solution of these technology problems.

- Identify other government organizations that share similar technology needs and time lines and obtain funding commitments.

- Define and fund demonstration projects (hardware systems and field trials) that will make use of the new FPA capability.

Based on the information presented in prior sections, a number of meaningful and achievable FPA technology goals can be set. Over the next 10 years, our studies suggest that the Air Force should commit to a FPA development program that takes advantage of both technology breakthroughs (uncooled arrays and quantum well devices) and incremental improvement paths. Suggested milestones include the following:

- Demonstrate a 2000 by 2000 MWIR FPA (may be achieved commercially, without AF).

- Demonstrate a 1000 by 1000 LWIR FPA.

- Reduce pixel sizes:
  - Visible: 3.5 micron square (may require entirely new approach beyond CCD technology)
  - MWIR: 10 micron square
  - LWIR: 20 micron square
- Demonstrate 1,000 frames per second in all bands (Visible, MWIR, LWIR) in 640 by 480 format or greater for specific problems that require classification of high-speed targets and signatures (may already be available in visible).
- Demonstrate specialized FPAs for IR multispectral applications. Example approaches include:
  - Multilayer HgCdTe with layers tuned to the specific bands for simultaneous 2 or 3 color band imaging sensing.
  - Fixed-tuned filters on-chip, plus electronic band-selection (a device that can provide ~6 simultaneous exposures in specified bands, from a larger set of 40 to 100 MWIR or LWIR bands, at reasonable spatial resolution).
  - A tunable filter approach (a device that contains a large array of continuously tunable detectors; typically, the device would output, say, 6 user-specified bands over 6 readout cycles, and then repeat the process).
- Demonstrate low cost, lightweight, low volume cryogenic coolers.
- Investigate and develop the use of enhanced sensitivity (i.e., improved thermal isolation and increased thin film thermal sensitivity in monolithic structures) and uncooled technology for cost savings in a specific MWIR application.

6.2.2.2 Laser Radar

Introduction

Laser radar has many important applications such as wind velocity measurements, material identification, target ranging and tracking, terrain following/terrain avoidance, and target detection. Laser radar can also aid in target recognition by:

- High range resolution imaging
- Two-dimensional imaging (angle/angle), where the laser is used as an illuminator for a TV type imager
- Three-dimensional imaging
- Target vibration/motion measurement
- Target reflectivity at various wavelengths
- Target polarization response and target speckle characteristics

In addition, gas cloud, or material identification, can be accomplished by differences in reflectivity or emission as a function of wavelength. DIAL is one technique. Materials can be identified, whether in a gas, liquid or solid form. Shorter wavelength lasers can also cause fluorescence, another material identification possibility. Laser radar can be used to accurately assess aircraft velocity and to look for obstacles. Terrain following (TF), terrain avoidance (TA), and obstacle avoidance (OA) are some of the more interesting laser radar applications for low altitude flight.

Solid state, wavelength tunable lasers are important for all of these applications and will be available in the future (see Directed Energy Panel Volume).

From a safety point of view, it is desirable that we use laser wavelengths beyond 1.4 μm, or below about 0.35 μm. The worst safety hazard from a laser comes from focused light that burns the retina. Above 1.4 μm absorption in the eye becomes significant enough that light does not reach the retina. There is a small UV window below 0.35 μm in which the eye absorbs light, but the light is transmitted through the atmosphere. At long wavelengths, absorption is very rapid and occurs at the surface of the eye.

Description of Applications

Wind sensing by laser radar is useful for many Air Force applications. These include targeting with guns and unguided munitions, as well as dropping munitions. Other applications include safety of flight applications such as detecting microbursts near airports, and detecting vortices from other aircraft. Aircraft velocity can be measured with a very small, very short range laser radar. Upcoming turbulence can be detected and the aircraft can compensate for turbulence before reaching it. This not only creates a smooth ride, but greatly extends the lifetime of the aircraft wings. These are commercial applications, which can create a large enough market to drive down laser radar prices. Vortex detection at an airport means closer spacing is allowed among the aircraft and that can mean large savings in fuel for commercial carriers. For wind sensing, a 2 μm laser radar is a likely candidate. This could consist of Holmium pumped by laser diode. Laser diode systems will become available without the need to pump another solid state material. Coherent systems are needed for most applications, since Doppler velocity is desired.

Another "soft target" for Air Force laser radar is a gas cloud. DIAL can be used to identify materials and can be used in the counter-proliferation thrust. This can also have commercial applications in pollution monitoring. It can also identify poisonous gases or could be used to detect telltale signs of a target. If a diesel generator is near a target, its exhaust might be detected. If certain chemical substances are given off by a target, they could be detected. These gas cloud detection schemes can also be applied to determining the material characteristics of target surfaces. Another benefit of a wavelength tunable laser radar is that certain wavelengths may transmit better through obscurants. For example, 1.5 μm will be greatly attenuated by fog, oil, and smoke, but 3.5 mm laser radar radiation will penetrate it easily.

Surface smoothness of an object can influence the polarization of the returned signal. If radiation is reflected off of a smooth surface, a major difference in the return polarization will result. That is, one polarization will be reflected more than the other component of polarization.

Rough surfaces will tend to have diffuse scattering, and both polarizations will be returned, no matter what illumination is used. Therefore, polarization can be a factor in determining target surface smoothness. Speckle statistics can also be influenced by target surface roughness. This is a complex area meriting further investigation.

For low altitude flight, wires can be a real hazard. Laser radar is an ideal method to detect such wires. Microwave sensors are at a real disadvantage for the same reason that they penetrate weather. The wavelength of the radiation is large compared to one wire dimension, so major scattering often does not occur. FLIRs will see wires under some conditions, but generally only at short range. Control of the illuminator is very helpful for the laser radar. Wires are thin enough that at most ranges the thickness of a wire does fill the detector in angle space. This means a degradation in signal to noise compared to a filled pixel. With control of the laser illumination, sufficient signal to noise can be generated at operational ranges under most weather conditions.

Relationship to Key Air Force Missions

Laser radar can accomplish many critical Air Force functions, as discussed above. These include target recognition, target detection, wind profiling for air drop, safety of flight, and as a FC adjunct sensor, and TF/ TA/ OA. Target recognition can even be accomplished in some cases with partial target obscuration. A wavelength tunable laser radar will have an improved probability of target recognition with obscured targets.

Relationship to Commercial Developments

Laser radar is a likely safety-of-flight sensor for commercial aircraft. It can detect microbursts at a landing and therefore can be a great safely adjunct. It can also detect vortices near an airport. This can allow better spacing of aircraft on landings and take off. Weather prediction can be aided using global laser radar systems, probably on satellites. Laser radars may be used in the future for collision avoidance in automobiles by placing them in the front of cars to detect approaching obstacles. High speed rail advocates have looked at laser radar for obstacle detection. Small obstacles on the track could derail a train. Some of these obstacles are too small to be reliably detected by microwave radar. One concept has the laser light transmitted through fibers placed along the rail lines. This allows bending around corners, and over hills.

Recommended Development Plan

Low rep rate laser radar needs to be developed that can conduct the designator function, as well as identify targets. Then wavelength tuneability needs to be inserted into the system, eventually in both coherent and incoherent laser radar form. Work needs to be done over the next ten years at a rate of about $1.5 M per year. A specific effort is required above the tech base to address target recognition. Another specific effort is required to develop a short range three-dimensional imaging laser radar seeker for all-weather precision strike (in conjunction with a high G missile). Each of these are efforts a few years in duration. The estimates of required funding are $3M per year for the combat ID system and $4M per year for the inexpensive, packaged seeker.

6.2.2.3 Space Fed Optical Phased Array Technology

Description of Technology

Optical sensors currently are burdened with heavy and complex gimbals. Optical phased arrays are an enabling new technology that makes possible simple, affordable, lightweight, optical sensors having very precise stabilization, random-access pointing, programmable multiple simultaneous beams, and dynamic focus/defocus capability. These arrays are space fed. An optical beam is transmitted through the phase shifter array, or is reflected from the array, and a phase profile is imposed on the beam. The optical phase shifters consist of electrically addressable liquid crystal gratings. Low voltage (less than 10 volts) is used to address these phase shifters. Since large-angle phased array beam steering requires phase shifter spacings on the order of a wavelength, addressing issues make one-dimensional arrays much more feasible than two-dimensional arrays. Crossed one-dimensional phased arrays can deflect a beam in both dimensions. Optical phased arrays with apertures on the order of 4 cm by 4 cm have been fabricated for steering green, red, and 1.06 μm radiation. Much larger apertures are feasible. Steering efficiencies of 57 percent at about 4 degrees and 85 percent at about 2 degrees have been achieved with switching times on the order of a few msec. Microsecond agile switching times are feasible. Optical phased arrays using liquid crystal phase shifters are becoming available. Because of the grating nature of the devices, they are ideal for steering monochromatic laser radar beams. These devices will greatly simplify beam stabilization as well as pointing, resulting in a much lower cost for high performance, stabilized optical sensors. Dynamic focus/defocus has also been shown, as well as multiple beam fanouts. Both new capabilities will simplify optical design and allow new sensor concepts to be implemented in a practical manner. Concepts have been developed to apply optical phased array technology to laser radars and to their passive acquisition sensors. A potential near-term application of phased array technology in passive acquisition sensors is microscanning. Large angle scanning of passive acquisition sensors can be accomplished using optical phased arrays if the spectral bandwidth is restricted. If these passive sensors employ high quantum efficiency detectors, then the sensitivity will be similar to state-of-the art scanning sensors. Use of optical phased arrays will enhance the development of active sensors and dramatically reduced their mechanical complexity. Dramatic cost savings for high performance laser radars will occur as optical phased array technology becomes available. Performance increases will be possible through the use of random access pointing anywhere in the FOV, simple fine stabilization, dynamic focus/defocus control, and beam fanout capabilities. Future growth areas include an adaptive optics layer for laser wavefront correction and atmospheric compensation, and for optical pattern recognition enhancement utilizing phase templates on either the transmit and/or the received beam.

Relationship to Key Air Force Missions

Optical phased array technology will have a dramatic impact on Air Force and commercial optical systems of the future. This will be a performance impact and an affordability impact. From a performance point of view, optical phased arrays will allow precise random access pointing of optical systems without undue mechanical complexity. It will be possible to point to about one part in one hundred of a diffraction limited spot size. It also should be possible to use an adaptive optics layer for correction of optical errors both in the system and in the atmosphere. Also, the fact that a single beam can be split into arrays of multiple beams will allows a number

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of new systems applications. Optical phased array apertures will allow the cost of high performance electro-optical systems to approach the cost of low or moderate performance systems.

Relationship to Commercial Developments/Applications

Commercial and Air Force display technology is similar to the liquid crystal based optical phased array technology. It should be possible to leverage off of this large commercial market. In addition, there are commercial beam steering applications. For example, there are telephone applications involving switching between fibers in a cable. With the multiple addressing approach, it should be possible to have a single beam in and then choose different sets of fibers to receive the signal. Also, commercial communications activities for satellites may use optical communications. This is a method to steer the beams from satellite to satellite.

Impact on Affordability

Cost should eventually be close to the cost of display technology. This means less than $1000 per large area device. Surface smoothness will be required in the near term that is more severe than that required by display technology. Later, however, an adaptive optics layer should alleviate that requirement. The device will not have to be flat because an adaptive optics layer will effectively remove any surface variation. Currently, highly precise gimbals are by far the biggest cost item in high performance EO sensors. Optical phased array technology should change that. This will greatly expand the affordability of EO systems as sensors, communication, or countermeasure devices.

Recommended Development Plan

We recommend developing a 10 cm diameter device capable of steering both active and passive (3 to 5 μm) radiation. Response time of the device should be under 1 msec. The device should include a telescope and beam steering should occur over angles > 5 degrees, with efficiencies > 75 percent. As a goal, we suggest steering efficiencies of > 50 percent at 55 degrees. This will allow steering to the corner of a 90 degree by 60 degree field of regard. This device should then be placed in an EO system and tested. Sensor and countermeasure tests should be conducted. It is estimated this is a 3-year development effort, requiring about $5M, a rate of about $2M per year. This will develop a robust steering capability at the 10 cm aperture size. If tests are successful, a follow-on 20 cm device should be fabricated with the same efficiency goals. Eventual steering efficiencies should rival microwave phased arrays. A separate 6.2 effort of about $500K per year should be sponsored to investigate some of the more difficult aspects of the technology, including broadband beam steering and steering at rates > 10 kHz. This 6.2 effort should be a 5- to 10-year effort.

6.2.2.4 T/R Module Based Optical Phased Array

Introduction

Space fed optical phased array technology has been demonstrated over reasonable size devices, and has potential for relatively near term system application. From a graceful degradation point of view, there are attractions to the T/R module based implementation of optical phased

arrays. Also power scaling on such an implementation should in theory be easier than with a monolithic source and space fed optical phased arrays. Scaling T/R module based phased array technology to optical wavelengths is however *very* challenging. This section will specify some of the challenges that must be overcome so that this technology can become reality.

Description of Technology

While complete azimuth and elevation coverage is desirable, something less, such as a 60 degree elevation coverage is quite useful. This depends on tactics employed by the warfighter. These are the same constraints in the multifunction, modular EO systems described in Section 5.2.6. Functions of this system include laser designation, covert high bandwidth communication, target detection (both A/A and A/G), target ID (both A/A and A/G), missile warning, and IRCM (possibly either smart jamming or sensor damage). If designing for a six-module system, then each module must cover a 60 degree by 60 degree solid angle. A four-aperture system requires 90 degree coverage in azimuth. Elevation coverage, as stated earlier, really depends on tactics and must be worked with the warfighter. Even in a four-module system, a 60 degree elevation coverage could be assumed. This elevation coverage implies designation capability will be lost briefly when the pilot turns sharply to return home after releasing laser guided ordinance, but as soon as the aircraft approaches level flight designation capability returns. The laser guided ordinance should be able to coast for the brief turning period. Limited elevation coverage also means that the pilot will not see a missile attack from the top or bottom of the aircraft. These are not high probability attack aspects.

There are two distinctly different problems to be considered. One is for the passive sensors and the other is for the active sensors. Unless true time delay is implemented, broadband optical beam steering is difficult. Most passive EO sensors are broadband. A large blur, occurs therefore, at the focal plane if a phased array is used to steer the broadband radiation. There are some approaches that may mitigate this problem, but the steering of broadband optical energy by imposing a phase shift is fundamentally more difficult than steering narrow linewidth optical radiation. A multifunction optical system must address both problems, at least at the system level. One approach would be to detect the radiation at each module, without ever transmitting the radiation to an optical focus. There would be no focal plane in the system, and the Fourier transform would be taken after detection. For a T/R module base optical phased array concept, the passive sensor mode is the proper choice. Digital deconvolution of multispectral data is a potentially promising approach to be used with a focal plane based concept.

Steering active radiation requires T/R modules on the order of the size of the wavelength to be steered. A general rule of thumb is modules that are at half wavelength spacings. Some microwave radar phased arrays go even farther because from an oblique angle the effective T/R module size appears to be reduced. If wavelengths from 0.5 μm to 5 μm are considered, then T/R module sizes from 0.25 μm to 2.5 μm are required. If the field of regard (steer over a smaller angle) is restricted, then the larger modules are acceptable, but more modules are required for complete coverage. From a sizing point of view, we should consider designing modules that are one or two microns on a side. Current detector array technology tends to be at a 25 to 50 mm pitch. Surface emitting diode array technology must be restricted to the vertical surface emitters if micron size optical pitches are to be realized. Addressing this development will also be very challenging.

Relationship to Key Air Force Missions

A graceful degradation, conformal system with no moving parts that can do A/A and A/G target detection and ID, covert laser communication, and missile warning and can counter IR missiles would have great impact on Air Force missions.

Recommended Development Plan

Much of the technology required to implement this plan is in the 6.1 stage. There are, however, a number of very interesting 6.1 technologies to be worked as part of the development of this technology. At this time, there does not appear to be any work attempting to place phase shifters on the end of vertical surface emitting diode laser arrays and then steer the output beam. Including an optical receiver in a vertical surface emitting diode array is another challenging technology. This might be done either by using the actual laser diode in a receive mode, or by attempting to have a separate detector in the same unit cell. Fundamental work to attempt single devices that can be laser transmitters and laser detectors, even on a large individual diode, would be very valuable. Building T/R modules in a small array of maybe 10 by 10 or 100 by 100 and steering them initially over a small angle will be a challenge, but it is a necessary step in the process. Initial T/R module size could be increased above the micron level size to conduct feasibility experiments. The associated passive sensor concept is another challenging technical area, independent of the laser receiver challenge. The method of blending the passive and active sensor concepts together needs to be addressed. The multifunction concept requires additional basic work. A wavelength tunable active system needs an OPO on the output of each vertical surface emitting diode. Making an array of OPO diode lasers is another required development. A small team of people (5 or 6 researchers) and on the order of $1M per year should be considered for this effort.

6.2.2.5 On Chip Tunable Sources and Filters

Technology Description

On chip tunable optical sources and filters are of great importance to multiprocessor interconnect, phased-array radar, multisensor fusion and information distribution applications. Tuning ranges cover broadband for wavelength multiplexed signal processing applications to narrow-band for optical RF applications. High-power, broadband tunable solid-state laser sources such as the Ti:sapphire, Cr:LiSAF, Forsterite, Cr:YAG and Co:MgF$_2$ cover wavelengths ranging from the near to the far infrared. The difficulty with miniaturization of these laser systems is the need for intracavity tuning elements and high-power optical pump sources. However, miniaturized, narrow-band tunable (on the order of a few to hundreds of gigahertz in optical frequency) versions of these lasers are in the early stages of development. The difficulty with the size reduction technology is the ability to achieve output powers approaching more than the few milliwatts required for long distance signal transport in guided wave systems, such as is required in field antenna remoting, as well as short distance signal transport in freespace systems, such as is required in laser radar and tracking systems.

The ability to achieve solid-state narrow-band tunable microcavity lasers is a direct result of the capability of producing very high-power semiconductor diode lasers, which are used as the optical pump sources for the solid state lasers and eliminate the need for bulky flashlamp

pumped systems. Dielectric mirrors can then be directly deposited on the laser crystal to form the cavity and the size of the overall laser reduced to less than 1 cm³. Narrow-band tuning elements can be incorporated into this small volume. Tuning is achieved by acoustical, thermal, or mechanical techniques. Acoustical, or acousto-optic, tuning is the fastest of these techniques with speeds approaching nanosecond time-constants. However, acousto-optic tuning requires high-voltage sources and is limited to tuning rages on the order of a few GHz of optical frequency. Thermal tuning is the simplest and most robust approach and can achieve tuning ranges of 100 GHz; however, it is limited by tuning time-constants on the order of seconds to milliseconds. Mechanical, or electro-mechanical, tuning is based on electrostatically deformable mirror elements. These elements are capable of tens of GHz tuning ranges with applied voltages of a few tens of volts. However, these elements are difficult to fabricate and have tuning time-constants on the order of microseconds.

Alternatively, broadband wavelength tuning has been readily achieved in both semiconductor and glass-doped substrate waveguides. Broadband wavelength tuning ranges of 2 to 50 nm using thermal or current injection control have been demonstrated using branching and distributed feedback structures. Digitally tunable semiconductor laser arrays are also available. Modulation/tuning rates for these lasers approach multi-GHz speeds since they rely on current injection. A key parameter for these integrated laser sources is their side-mode suppression ratio (SMSR). SMSRs on the order of 20 dB or better are required for dense wavelength division multiplexed (WDM) applications. These lasers are of great importance for wavelength conversion operations. Predominately, these lasers have been limited to the wavelength region of established semiconductor laser technology, such as 850, 980, 1300 and 1550 nm regions. With the advent of doped glasses, GaN and related large bandgap materials as well as nanoparticle structures, windows in the visible to ultraviolet should become available in the near future.

Tunable filters have evolved from bulk optical techniques similar to dispersive gratings and interferometric components such as Fabry-Perot cavities. These filters have been brought down to the scale of the microcavity lasers using state-of-the-art photolithographic, microfabrication and micropackaging procedures. These filters include acousto-optic tunable filters in lithium niobate, high-finesses fiber Fabry-Perot filters, distributed Bragg reflectors in optical fiber or substrate waveguides and waveguide grating routers. All of these optical filters are typically for use in the broadband, that is, optical wavelength separable, spectrum of light. Typical performance parameters include: tunable wavelength range (2 to 50 nm), bandpass bandwidth (0.1 to 2 nm), free spectral range, channel crosstalk (-20 to -30 dB), and tuning speed (ms to ns). Tunable filtering in the narrowband, gigahertz RF domain is usually accomplished by first optically heterodyning the incoming laser signal with a coherent local oscillator and then using standard RF electronic techniques to recover the information.

Relationship to Key Air Force Missions

Tunable filters and sources are a basic technology required in many high-performance and/or high-priority missions. The ability to optically tune both filter and source, either in the optical wavelength domain or the RF frequency domain, creates a functional element that can be used for both point-to-point and in generalized local or wide area communications network environments. Tunability permits the system designer to incorporate WDM into system design.

Tightly controlled wavelength registration permits the system designer to use coherent detection for multi-gigahertz RF throughput on individual wavelengths.

The ability to integrate these devices (filter and source) on a chip will have a tremendous impact on system design. It means that the system designer can use WDM and coherent detection capabilities, both powerful interconnection technologies, as a basic architectural tool at the lowest level of design in high performance systems.

Tunable sources and detectors for optical interconnects will permit greater flexibility and performance in system design, while integrated, on-chip components significantly reduce system weight and allow for mass production, reducing component costs. The development of this technology will provide:

- Increased data transfer rates and hence overall system throughput.

- Systems that are more reliable by permitting alternate routing (self healing) and wavelength re-use.

- Real-time computational intensive systems, especially those dealing with multiple threats.

- More secure systems by using multiple wavelengths for coding enhancement and transmission path separation.

Tunable sources and filters combined with optical fiber cable technology will significantly reduce system weight and increase performance due to its immunity to electromagnetic interference capability. Such characteristics, combined with the freedom of optical tuning, will find significant uses in the following Air Force programs:

- F-22 network control of Avionics system

- Radar antenna remoting and networking

- Optical Steering of Phased Array Radars

- Bandwidth enhancement of Rivet Joint aircraft for multiple threat environments

- AWACS Upgrade

- J-Stars (performance upgrade)

- Sensor fusion systems and massively parallel processing as will be needed in virtual reality systems for training and readiness

Relationship to Commercial Development

There is great commercial benefit for this technology. The integrated semiconductor technology for tunable sources and filters is driven primarily by the telecommunications industry in their quest to develop very high density and very high speed interconnects that take advantage of the promised terahertz capacity of optical fibers. This is evidenced by the proliferation of publications on the components listed in the description of technology section above. The requirements of commercial industry are for broadly tunable sources and filters for local and wide area distribution interconnects for data transfer environments that include traditional circuit

switching of telephone services as well as very bursty traffic associated with packet switching such as is encountered on the Internet.

As commercial services grow, such as cellular phone service, video on demand and home educational services, the impact on integration, cost and reliability will also grow. However, these corporations are not investigating the military requirements for RF signal generation, high optical power generation, temperature range and stability. Thus, the Air Force must continue to participate in this technology to extend the performance of commercially developed components.

Impact on Affordability

Leveraging on commercially developed tunable semiconductor technology for WDM systems is very cost effective and will produce the most reliable components.

Leveraging on commercially developed tunable solid state technology for narrowband optical RF technology for coherent communications is not an option as the commercial industry has only a small interest in this area.

Recommended Development Plan

A key opportunity is available to leverage off the current developments of commercial industry. It is, therefore, recommended that the Air Force identify the key performance requirements of their systems and match them with the performance of currently available commercial components and then investigate the potential for extending the technological performance of these components into the military requirement domain.

Beyond these component developments, efforts in control system development for improved optical frequency stability and registration are required to maintain system-wide compatibility of multiple channel processors and users.

Also, continued efforts in packaging to improve temperature range performance and reliability are required to meet military performance.

On the basic 6.1 level, development of new materials in the area of nanoparticles and polymers to create compact, microstructure lasers that are lightweight and operate in wavelength regions not currently covered by viable semiconductor alloys would be of great interest to the Air Force.

6.2.3 RF Apertures, Components, and A/Ds

The current vision for next generation tactical airborne architectures applies broadband phased arrays shared between radar, electronic support measures, ECM, and communications functions to minimize the number of antennas on an aircraft, thus reducing overall weight, volume, and cost. This concept also provides enhanced performance by making an active electronically scanned aperture available for all these functions. A broadband multifunction array provides the system's flexibility needed for selection of the optimum frequency, power level, radiation beam shape, beam update rate, and so forth, based on specific modes and the mission environment. An operational mission applying shared aperture technology is illustrated conceptually in Figure 6-5.

Labels in figure: Weapon Data Link, Narrowbeam ESM, Covert Data Link, Air-To-Air Radar, Self-Protect/Escort Jamming, SAM Site, Air-To-Ground Radar, Missile Approach Warning, Programmable Decoy, Threat Warning
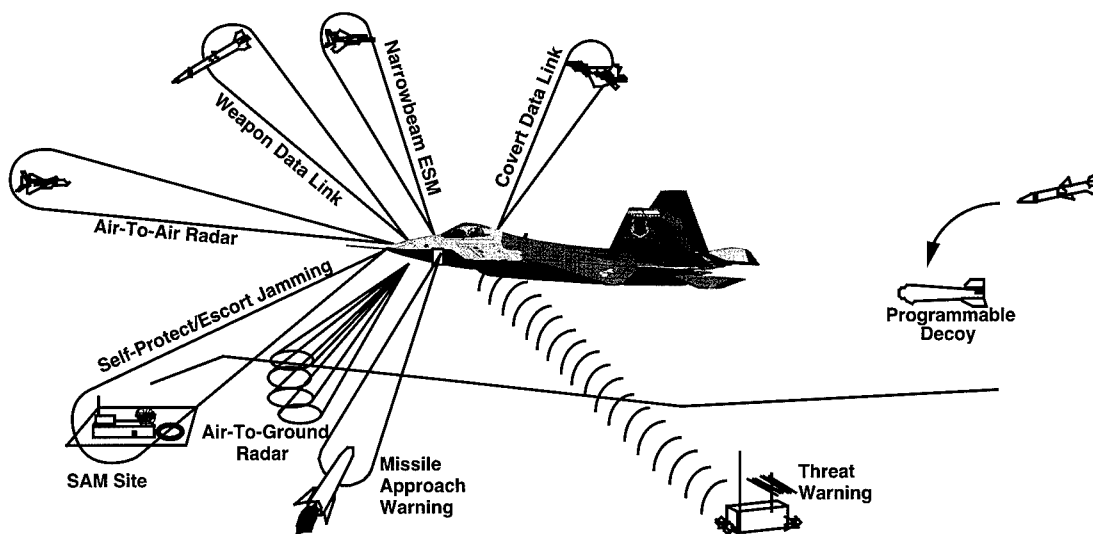
- **Greater Mission/Role Flexibility**
  - **Multifunction Avionics**
  - **Adaptive Mission Planning**

- **Increased Engagement Effectiveness**
  - **Reduced Timelines**
  - **Synergistic Functions**
  - **Enhanced Countermeasures**

- **Improved Survivability**
  - **Reduced Observables**
  - **Improved Situation Awareness**
  - **Enhanced Self Protection**

- **Reduced Cost and Weight**
  - **Shared Apertures**
  - **Common RF and Digital Components**

Figure 6-5. Integrated Multifunction System Benefits

In the future, system sensor suites will employ thin conformal antenna structures incorporated in the aerodynamic surfaces (smart skins) of advanced airborne platforms. The structures will provide multifunction aperture operation and will contain an array of high density microwave/millimeter-wave "tile" modules using monolithic GaAs and InP circuit technology. Conformal arrays will become practical in a low observable format with the realization of the promise offered by advances in high power density heterojunction bipolar transistor (HBT) integrated circuits. With proper R&D focus, electrical, thermal, and mechanical interface technologies can be developed to move from today's planar microwave module topology to the three-dimensional structures of tomorrow's "tile" architecture.

The continued and rapid advancement of digital technology, combined with GSPS clock rate, 8 bit and greater ADC, will allow earlier (closer to the system front end) digitization of the signal originating from each system sensing element. For example, the sensing element could be the individual radiating elements of a phased array aperture. Early digitization and high speed preprocessing can facilitate the implementation of pulse compression, multiple simultaneous beam formation, and digital I and Q channels prior to the normal coherent digital

processing performed by today's advanced electronics systems. Higher performance, lower cost systems will result and will provide increased flexibility inherent in software based architectures.

Each of the above technology areas will be discussed in the following sections.

6.2.3.1 Broadband Integrated Multifunction Shared Apertures

Technology Description

Over a number of years, avionics systems have been evolving toward more integrated "open" architectures. Today's typical weapon system has integrated multifunction displays and controls and in some cases, such as the F-22 aircraft, a common processor for all sensor functions. The next logical step is to integrate the "front-ends" (apertures and support electronics) of avionics systems so multiple functions can share common resources. AESA technology has progressed to the point where it is now feasible to produce integrated multifunction apertures (IMAs) that will perform all RF functions (radar, EW, and CNI) across broad portions of the microwave frequency spectrum. For example, the RF spectrum from 500 MHz to 18 GHz, which is typically used by airborne weapon systems, can conceivably be covered by three multifunction apertures: 500 MHz to 2 GHz, 2 GHz to 6 GHz, and 6 GHz to 18 GHz. These apertures would perform all of the RF functions that fall within their operating band.

An IMA that covers the high band, 6 to 18 GHz, is the most challenging but also offers the highest potential for dramatic life-cycle-cost savings. Based on recent studies, a high band IMA that could be used in future applications such as JAST and retrofit applications on existing aircraft such as the F-15 or F-16 might have the following general characteristics:

- Open architecture with multiple independently scanned beams for simultaneous, interleaved functions

- High power, high efficiency radar operation across all of X-band

- Low noise, high gain ESM across the full 6 to 18 GHz band

- Lower power ECM and CNI functions across critical portions of the 6 to 18 GHz band

This aperture could be constructed from a set of common building blocks (T/R modules, high density power supplies, and beam steering computer) and would be tailorable to particular applications. Tailorable characteristics could include aperture size, array grid shape and size, number of subarrays (independent beams), and polarization. With this degree of tailorability, a common aperture approach could cover applications from conventional aircraft with very little RF functionality to low observable aircraft with high degrees of RF functionality. The open architecture design would allow higher performing technology (such as higher power, higher efficiency, wider bandwidth, etc.) insertion as it became available, thus mitigating technology obsolescence.

A key part of the IMA concept is a "smart" resource manager that can adaptively allocate aperture and "back-end" resources to meet critical mission timelines. Previous studies and simulations have shown this resource manager can be "rule based." Control of assets at millisecond time increments provides adequate control for most timeline requirements.

Relationship to Key Air Force Missions

Air Force missions require a broad spectrum of RF functionality. High efficiency radar is usually a driving requirement, but passive RF for threat warning and precision targeting can be essential for certain missions. Some missions would be benefited by on-board ECM for self-protection or escort support for other aircraft. Also, the capability for covert communication at the higher microwave frequencies could provide improved mission effectiveness. A common multifunction aperture that can synergistically provide all of these capabilities would potentially be of great benefit to the Air Force.

In the past, primarily because of federated avionics architectures, expanding existing RF functionality was deemed to be unaffordable. This has led to the current emphasis on low observable platforms with limited RF functionality and as much off-board support as possible. It was envisioned that this was the only way to achieve affordability. In particular, on-board ECM was generally not seriously considered because of its perceived high cost. Recent studies have shown, however, that on-board ECM capability can reduce low observability requirements, which are a major aircraft cost driver. There is also the question of the ability or desire to maintain very low levels of observability after the first few days of a war. Assuming that multimode radar and ESM are required, a multifunction shared aperture approach can also provide additional ECM functionality, and the attendant survivability benefits, at very little increase in cost.

Relationship to Commercial Developments and/or Applications

The broadband Monolithic Microwave Integrated Circuits (MMICs) and low cost manufacturing processes required for a multifunction aperture are also being proposed for other DoD and commercial applications. Multibeam AESA antennas for commercial communication satellites and gateways are strong candidates for low cost technology insertions. It is unlikely, however, that commercial applications will require the multifunctionality needed for Air Force missions.

Affordability

Recent studies have shown that, depending on the degree of functionality required, life-cycle-cost saving for JAST avionics over 20 years can be as much as $5B to $12B through the application of common IMAs. The larger savings is for aircraft that require full RF functionality (radar, ESM, ECM, and CNI) and spherical (all aspect) coverage for threat warning and self-protect jamming functions. Studies have shown that to implement such a system, using today's technology, would require about 32 apertures and a large complement of support electronics (transmitters, low noise receivers, etc.). Equivalent functionality and coverage using IMAs would require only 8 apertures and, since transmit and receive functions are inherent in AESA apertures, the supporting electronics would be greatly reduced. If the requirement for on-board ECM is eliminated, the savings would still be a dramatic $5B. In addition, further savings would result from the reduced cost of aircraft installation due to fewer apertures and less support electronics, and the attendant lower weight.

The above savings are for JAST aircraft only. If the common building block approach, described above, were applied to future AESA upgrades such as the F-15 and F-16, the Air Force could realize additional savings in areas of:

- Reduced development cost (common building blocks would apply to multiple applications).

- Reduced acquisition cost due to increased manufacturing volume of common components.

- Reduced upgrade cost due to inherent growth capability.

- Reduced maintenance cost due to increased reliability of AESA apertures.

- Reduced logistics cost (common support equipment, training, etc.).

In addition to the Air Force, other service components could realize substantial savings from use of common aperture building blocks. An upgraded F-18, for example, will have similar aperture requirements to the F-15 and F-16. Bombers, ships, national assets, ground installations, and even future submarines are considering the potential benefits of multifunction shared apertures.

Recommended Development Plan

The basic technology exists to develop broadband IMAs, but it has not been demonstrated. Current aircraft that employ electronically scanned array antennas use bandpass radome concepts to reduce their RCS outside of the typically narrowband radar operation. This concept will not work for IMAs where broadband operation is required to realize the full benefits of multifunction shared apertures. Future developments should therefore concentrate on building and demonstrating an integrated aircraft "forebody," consisting of a low observable, broadband (6 to 18 GHz), multifunction aperture and "clear" radome, that could be applied to JAST and other future/retrofit aircraft needs. Development of a robust resource manager to allocate system resources as needed to meet critical mission timelines should be an inherent part of this plan. The integrated forebody, along with "back-end" test assets and the resource manager, need to be demonstrated first in a rooftop environment and eventually in a test-bed aircraft to fully prove the multifunction, shared aperture concepts.

A strawman program plan and ROM cost to implement the plan for the 6 to 18 GHz IMA are as follows:

Phase I: Concept Definition Study   6 Months $1 to $2M

Phase II: Integrated Forebody D&D   33 Months $40 to $60M

   - Develop Aperature, Radome, and Resource Manager

   - Integrated Forebody Demo

Phase III: Rooftop and Flight Test   33 Months[4] $20 to $30M

   - Modify Existing "Back-end"

   - Rooftop and Flight Demo

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4. Phase III starts 12 months after Phase II and extends 12 months beynd the end of Phase II (total duration of Phases I through III is 51 months)

If funding allows, IMAs covering the other frequency bands (500 MHz to 2 GHz and 2 to 6 GHz) could be developed and demonstrated in parallel programs with the 6 to 18 GHz IMA. The development risk for these apertures, however, is much less than the 6 to 18 GHz aperture and could be delayed and incorporated in an EMD program.

6.2.3.2 MMICs for RF Aperture-Multifunction Shared Aperture, Broadband

Technology Description

MMICs are used for various applications in the microwave frequency domain from around 1 GHz to 60 GHz and above. Typical uses are as active components in the form of amplifiers (low noise and power), oscillators (stabilized and voltage tuned), and control elements (switches, limiters and phase shifters) and passive components such as couplers, power splitters and combiners. MMICs are fabricated using Gallium Arsenide (GaAs) semiconductor technology and are now being used in a variety of military and commercial programs.

AESAs for the BMDO Ground Based Radar (GBR), several classified Service and Agency applications, and the F-22 fighter aircraft are now under development. These radar arrays use GaAs MMICs to construct a T/R function (module) that drives individual radiating elements of the radar array. Although the MIMIC program has demonstrated an impressive advancement in capability, future defense system developments will require, for example in the power amplifier area, increased power outputs from today's 5 to 10 watts/MMIC to the range of 20 to 30 watts/ MMIC at X-band. Enhanced operating efficiencies, greater than 40 percent, will be required in order to reduce array size and improve performance. Figures 6-6 and 6-7 show the power and efficiency trends that can be expected over the next 10 years for X- and K_a-band devices if R&D funding is made available. Multifunction wideband RF system architectures are supportable by AESAs technologies and as such can provide radar, electronic support measures, and communication functions in a single aperture. Large reductions in weight, volume, and complexity can then be realized over the multiple apertures used on our current airborne platforms.

Technological advances are needed in several areas to support future mission roles and reduce acquisition costs of AESAs. MMIC processing facilities will need to convert to 150 mm diameter wafers from the 75 mm and 100 mm wafers presently used. Considerable advancement in GaAs processes and processing technology is required to provide MMICs with high yields at the increased levels of complexity and performance that have been projected to meet future system needs. High density microwave packaging will be required to reduce array size and weight. Advanced microwave device structures and microwave semiconductor materials are needed to provide higher output powers at greater efficiency than the present GaAs devices. Multifunction MMICs with RF, digital, and analog functions on a single chip will be needed to provide increased weapons system capability at an affordable cost.
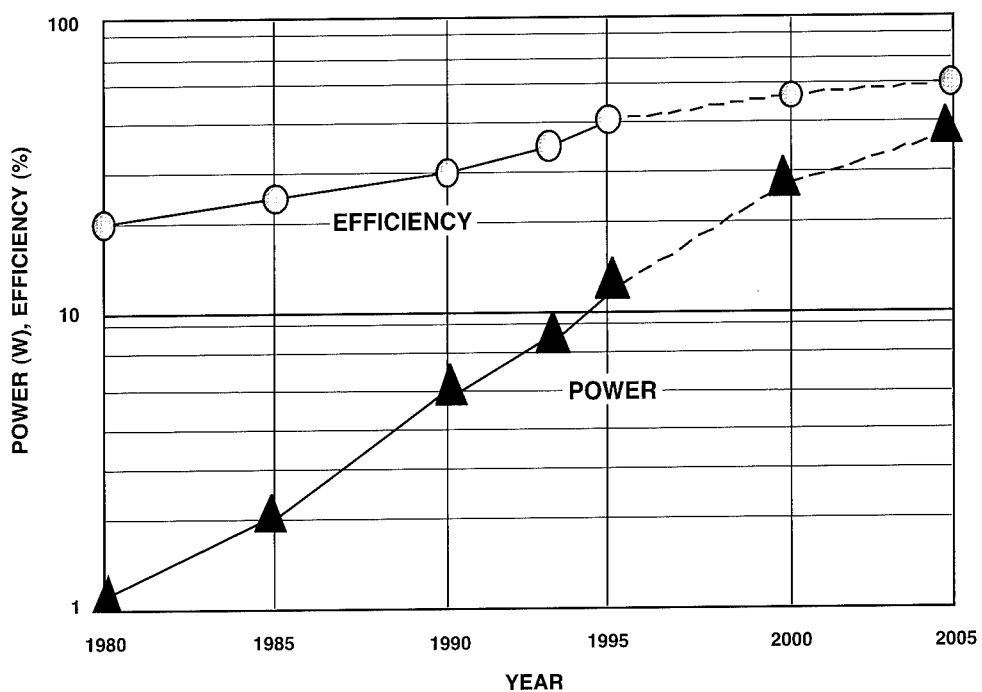
Figure 6-6. X-Band Power Amplifer Performance

Figure 6-7. K_a-Band Power Amplifier Performance

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Relationship to Key Air Force Missions

The Air Force is currently funding developments for AESAs for future A/A and A/G missions. These technology development activities directly support the F-22 program. The technology is playing an increasingly important role in the arena of towed and expendable decoys and A/A missiles that must seek and destroy stealthy targets. The development of small compact phased array systems based upon enhanced performance from MMICs and high density packaging will eventually lead to smart skins (conformal array) systems capable of providing full sector situation awareness on aircraft platforms. Compact millimeter-wave communications arrays will be enabled and will allow continuous information flow to and from high dynamic airborne platforms via MILSTAR satellites.

Relationship to Commercial Developments

Current commercial developments are in ground-based and satellite telecommunications with emerging applications in personal communications services, cellular telephones, and satellite-to-air relay communications. The Air Force applications require much higher performance in terms of bandwidth, output power, and operating frequency than the commercial uses. Although commercial MMIC and packaging developments will benefit in a significant way from the R&D activities and enhanced processing and manufacturing capabilities, commercial investments will be required to tailor the technology to specific large scale, cost-driven opportunities. Emerging systems applications such as higher frequency, broadband, wireless local area networks, personal communications services, satellite-to-air communications, and a variety of satellite based telecommunications services will take several years to be fully deployed and become operational.

Affordability Impact

The development of higher performance microwave devices will reduce parts count and simplify the assembly of T/R modules and high density microwave packages. This will allow a system of comparable performance to be procured for a lower cost or a system with increased performance to be procured for a more affordable cost. From a commercialization perspective, manufacturing experience, based upon traditional learning curves and ongoing cycle time reduction efforts, shows that large volume production of MMICs for commercial and military applications will lead to lower costs. Statistical quality control is more effectively instituted and production variations are minimized with large production bases.

Recommended Development Plan

Processing improvements continue to be needed to increase the yield, reliability and quality of MMICs. Expanding applications in military and commercial systems require further concentration upon cost reduction efforts, such as converting to 100 mm diameter wafers for present uses and eventually to 150 mm diameter wafers for future large volume manufacturing. Device and modeling developments are also needed to increase power output and efficiency of power devices and to further reduce the number of active devices used in AESAs. Continued emphasis on reliability studies is needed to assure dependable performance and to achieve longer operating lifetimes of MMICs.

New microwave semiconductor materials such as indium phosphide, silicon carbide, diamond, and so forth, must be researched and developed to provide the best power amplifier MMIC performance consistent with the needs of the next generation systems.

Advanced epitaxial deposition techniques must be developed to decrease the cycle time for the higher manufacturing rates forecast for future production programs. Production lithography processes for sub-micron device structures suitable for high rate production are also needed to support the advanced microwave device developmental efforts.

Continuing developments are needed to support microwave packages with high density multilayer microwave circuit boards and multichip, multilayer modules. Packaging technology efforts must continue to focus on the small footprint (less than a quarter of a wavelength on a side) T/R module tile architecture that is essential for conformal array implementation. Composites suitable for microwave packages are needed for hermeticity, minimum weight, and effective heat dissipation of power sources.

MMIC technology is currently viewed as a maturing industry that has demonstrated the potential for satisfying the Air Force requirements for future airborne platforms. A considerable tech-base capability has been demonstrated in all the development areas outlined above and is amenable for full development of efficient production processes to achieve the manufacturing rates needed by the Air Force. Even though the MMIC industry is viewed as maturing, many areas requiring an advanced R&D focus have been highlighted above.

6.2.3.3 Analog to Digital Converters

Technology Description

Over the last two decades, the rapid evolution of digital integrated circuit technologies has led to ever more sophisticated signal processing systems. These systems operate on a wide variety of "natural" or continuous-time signals, which include, but are not limited to, speech, medical imaging, sonar, radar, EW, instrumentation, consumer electronics and telecommunications. One of the keys to the success of these systems has been the impressive advances in the development of the ADCs that convert the continuous-time stimuli to discrete-time, binary-coded form. The large number of signal types has led to a diverse selection of data converters in terms of architectures used, bits of resolution achieved, and sampling rates employed.

Despite the variety in data converter systems, their performances can be summarized in a relatively few charts. One is shown in Figure 6-8, where ADC resolution (as stated by the manufacturer) in bits is plotted against sampling rate, f_{samp}. Over 100 converters, including experimental integrated circuits (ICs) and commercially available parts, are represented in the graph. One performance limitation that emerges from the plot indicates that approximately one bit of resolution is lost for every doubling of the sampling (clock) rate (indicated by the line on the graph). As technologies advance, the line moves slowly upward but the slope remains about the same. The -1 bit/octave slope can be explained in terms of aperture jitter, which is the uncertainty in time in which the amplitude of the input signal voltage is sampled (captured). Another limitation evident in Figure 6-9 is that the highest sampling rate attained so far is a few giga samples per second (GSPS). This limit is related to the ability of the comparator(s) to transition from sample-to-hold (regeneration time constant) mode and/or to transition from

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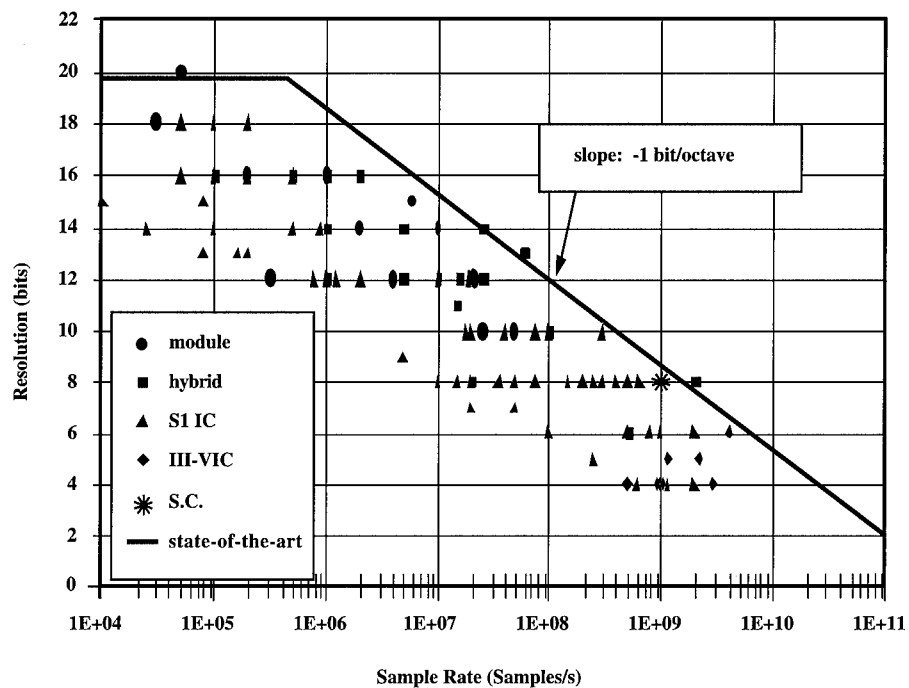
Figure 6-8. Survey of Analog-to-Digital Converters
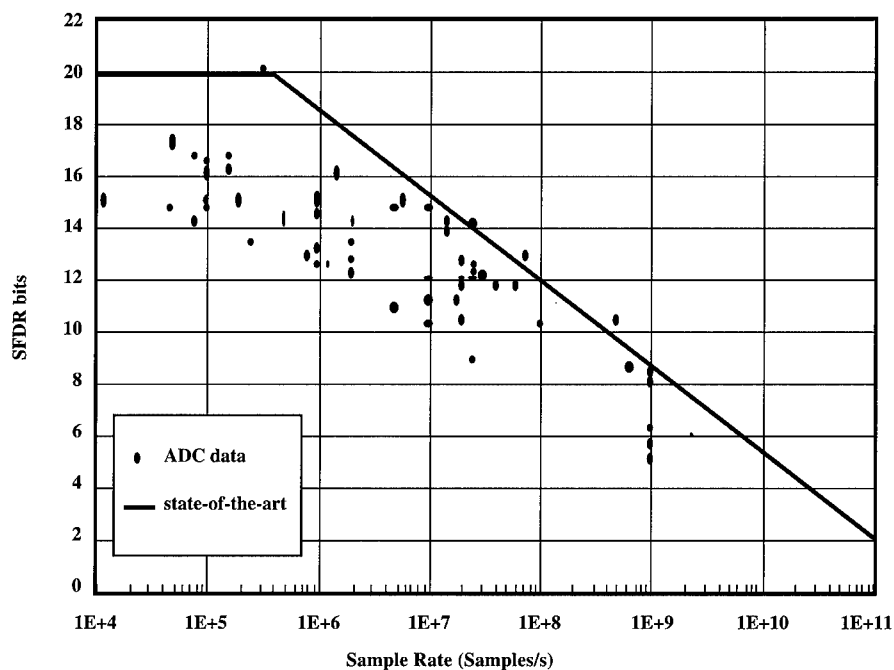
Figure 6-9. Spur-Free Dynamic Range Expressed as Effective Number of Bits

hold-to-sample (track recovery time) mode and still make an unambiguous decision regarding the relative amplitude of the input voltage. This can be directly related to the performance of the device technology used to fabricate the ADC, in terms of the unity-current-gain frequency, f_T, and/or device parasitics. At lower sampling rates, the maximum resolution appears to be limited by white noise found/generated at the ADC input stages.

A/D Converter Characterization

There are a number of ways in which to measure and compare A/D converter performances. Primarily we are interested in determining the resolution in bits for a given sampling rate, and, in an increasing number of applications, the power consumption is also important. Resolution can be determined both quasistatically and dynamically: quasistatic measures include, but are not limited to, differential nonlinearity (DNL) and integral nonlinearity (INL), while dynamical measures include signal-to-noise ratio (SNR), spurious-free dynamic range (SFDR) and noise power ratio (NPR). These last three quantities are determined from a spectral analysis (usually in the form of an FFT) performed on a sequence of A/D converters' output samples. The most significant figures of merit are probably SNR and SFDR because (1) the dynamic performance is most important for high-speed applications, (2) SNR and SFDR data provide a more accurate, yet general, indication of A/D converters' performance than the stated-number-of-bits used in Figure 6-1, and (3) SNR and SFDR have been universally accepted as performance measures.

SNR is defined as the ratio of the rms signal amplitude to the integral of the noise spectrum over the frequency band of interest (we will use the full Nyquist range, 0 to $f_{samp}/2$). The SNR in dB can be related to an effective number of bits, which we will refer to as SNR bits, by

$$\text{SNR bits} = (\text{SNR (dB)} - 1.76)/6.02.$$

Similarly, an effective number of bits associated with SFDR can be expressed as

$$\text{SFDR bits} = \text{SFDR (dBc)}/6$$

where the SFDR is defined as the ratio of the signal amplitude to the largest component (not the signal) of the frequency spectrum within the band of interest (again 0 to $f_{samp}/2$).

Performance Limitations

In order to determine the performance limits quantitatively, it is necessary to replot the data of Figure 6-8 according to the effective resolution as determined from either SFDR or SNR. Figure 6-9 shows the results using reported SFDR values (where available). A comparison of Figures 6-8 and 6-9 indicates that, when the population is taken as a whole, the effective resolution expressed as SFDR bits appears to be roughly the same as the stated resolution (number of output leads). However, this is somewhat misleading because the variation in the quantity (stated bits - SFDR bits) for any given converter is ~0 ± 3 bits—a wide variation.

A similar graph can be constructed for SNR bits versus sample rate and is shown in Figure 6-10. A comparison with Figure 6-8 shows that, in general, the number of SNR bits is approximately 2 bits lower than the number of stated bits. This conclusion is supported by looking at individual A/D converters. The results of Figures 6-9 and 6-10 clearly show that relying only on the stated number of bits can be very misleading when evaluating performance.
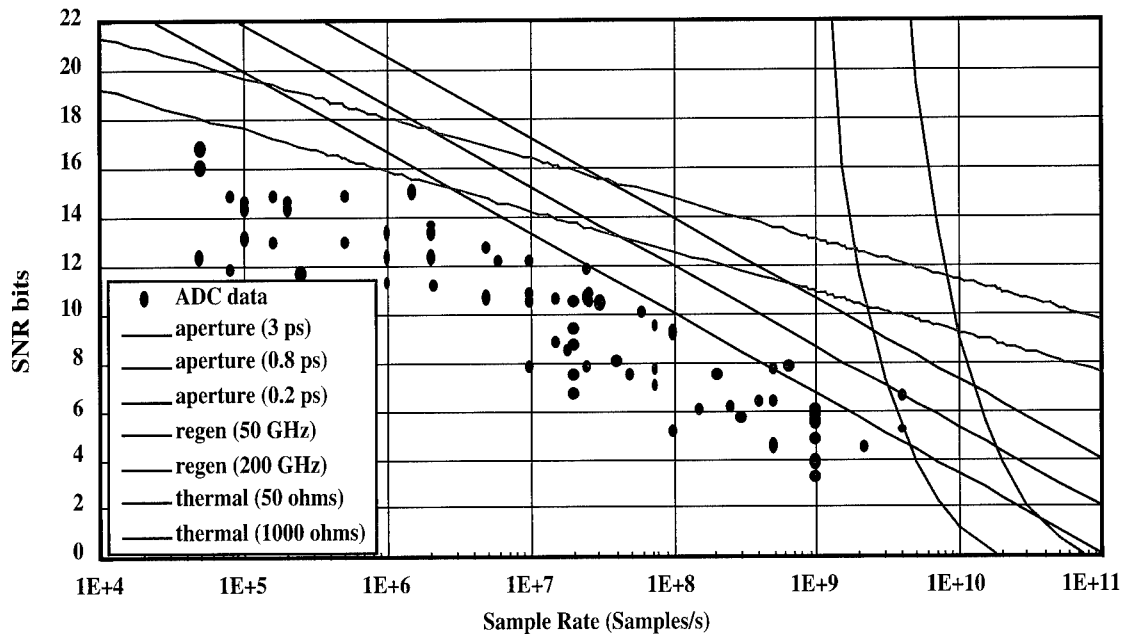
Figure 6-10. Signal-to-Noise Ratio Expressed as Effective Number of Bits

An examination of global performance limitations of the A/D converters indicates that the current state of the art is limited by (1) white noise roughly equivalent to the thermal noise associated with a $1k\Omega$ resistor for low (1 MSPS) sampling rates; (2) aperture jitter of 1 to 3 ps for a large sampling frequency range (1 MSPS to 4 GSPS); and (3) regeneration time constant corresponding to an f_T value of 50 GHz at the highest sampling rates. The aperture uncertainty effect gives rise to the -1 bit/octave slope and is the dominant limit because the range of affected f_{samp} values is so large.

To advance beyond present capabilities will require designs that achieve less than 1 ps of jitter and/or technologies that perform better than 50 GHz. There are reported HBT technologies that have achieved device performances in the range $160 \leq f_T \leq 190$ GHz; hence, one can envision an eventual increase in sampling rates of a factor of three or four beyond today's 4 GSPS.

A/D Converters Performance Over Time

It is revealing to examine the progress made in A/D converters' performances during recent years. It is evident from the graphs that little progress has been made over the last six years. Some reasons for this stagnation may be: (1) a technological (if not fundamental) aperture jitter barrier of 1 ps; (2) much of the recent research has been aimed at monolithic and, therefore, efficient A/D converters; (3) a recent and general de-emphasis on research and development; and (4) few application drivers.

Architectures

Current A/D converters are designed using a variety of architectures ranging from parallel (flash) which is the fastest, through integrating which is perhaps the most accurate but also the slowest. Most of the converters have been fabricated in some form of Si technology, while a few have been realized in GaAs-based and in InP-based technologies.

The flash architecture utilizes 2^{b-1} comparators, all of which sample the analog input voltage simultaneously and, therefore, this type of converter is inherently fast. The parallelism of this architecture has a significant drawback when high resolution conversion is desired, namely, the number of comparators grows exponentially with b. In addition, the separation (ΔV_{ref}) of adjacent reference voltages grows smaller exponentially. The consequences are: very large ICs, high power dissipation, difficulty in matching components, and the increasingly large input capacitance reduces analog input bandwidth. Most flash converters available today have < 8-bit resolution.

In order to overcome these problems, variations on the flash architecture have been developed that utilize relatively small numbers of comparators yet retain good speed. Examples that are capable of giga sample/s conversion rates are: the multistage, folding, and pipelined. Another approach for achieving high-speed conversion is to time-interleave two or more converters. This particular converter is "the exception that proves the rule" with respect to the overall lack of progress in improving A/D converters' performance. Specifically this A/D converter's system achieves 1 ps aperture jitter, but requires two hybrids, each with five LSI chips. The total P_{dis} = 40 W, which is roughly an order of magnitude larger than other contemporary converters.

An architecture that can trade speed for resolution is the combination of delta sigma modulation and digital decimation filtering. Delta sigma modulators sample the analog input signal at a rate that is many times the final (Nyquist) output rate and use feedback to suppress the quantization noise in the lower portions of the spectrum (relative to the delta sigma clock frequency). One advantage of this technique is that very few analog components are required. The challenge is that a very high speed IC technology is needed. Recently, ARPA has demonstrated an InP-based HBT (f_T = 70 GHz, f_{max} = 90 GHz) second-order DS modulator at a sampling rate in the 3.2 GSPS range and an oversampling ratio of 32 (Nyquist rate of 100 MSPS). This is the fastest DS modulator yet built.

Relationship to Key Air Force Missions

The Air Force uses A-D conversion in a wide variety of systems including radars, communications systems and electro-optic sensors in aircraft and missiles as well as in ground based systems.

Relationship to Commercial Developments

Current commercial developments are focused on communications and entertainment applications with digital radios, cellular telephones, personal communications services (PCS), digital satellite and cable TV receivers as the current leaders in anticipated demand as well as the most stressing designs. None of the commercial applications is likely to push A/D performance beyond Air Force needs in the foreseeable future.

Affordability Impact

As A/D converters become more capable, the general trend in sensor systems is to move the converter closer to the transducer and to eliminate more and more analog electronics. This trend toward early conversion from analog to digital signals has the effect of reducing the fraction of the system with historically increased costs while increasing the digital fraction, thus allowing that part to follow the declining cost curves of commercial digital processing technology.

Recommended Development Plan

The trend toward lower cost digital processing is likely to continue. Further increases in A/D converter speed and dynamic range will enable Air Force systems with full digital signal path implementations for electronic warfare and information warfare systems applications. These digital signal path systems can cost less both in life cycle terms and in acquisition costs if the development of high performance A/D technology advances fast enough to keep up with developments in digital signal processing technology.

In order to improve on the present state of the art in A/D converters performance, significant technical challenges must be met: (1) a reduction in aperture jitter to below 1 ps, (2) an increase in the maximum sampling frequency to beyond 4 GSPS, and (3) accomplishing both (1) and (2) while maintaining low power consumption, for example, < 5 W.

With respect to aperture jitter, only about one bit of overall improvement has been achieved over the last six years in both SNR and SFDR. The best effort was the time-interleaved A/D converters which achieved 1 ps aperture jitter. In addition, while significant progress has been made in achieving power-efficient A/D converters' designs, none of these efforts has gone below 2 to 3 ps of aperture jitter.

It would be timely, therefore, to investigate the basic noise mechanisms responsible for aperture jitter, and how they manifest themselves in particular A/D converters' circuits. Such an undertaking would involve examining very high performance IC technologies.

The achievement of ultrahigh sampling rates (> 4 GSPS) requires an ultrahigh speed IC technology. A particular combination of sample rate and resolution is 4 GSPS and 8-bits, and would be interesting to investigate because it "pushes the envelope" for both aperture uncertainty and sample rate (see Figures 6-10 and 6-11), and because its realization would also enable future ultrahigh-speed signal-processing systems.

Finally, a study of power-efficient A/D converters' designs would concentrate on A/D converters' architectures that minimize component/device count. In addition, scaling down of transistor sizes to reduce "per capita" power consumption would also be important.

Without appreciable efforts in these directions, it appears that very little progress will be made by the turn of the century in increasing the resolution-sampling rate product of A/D converters in general.
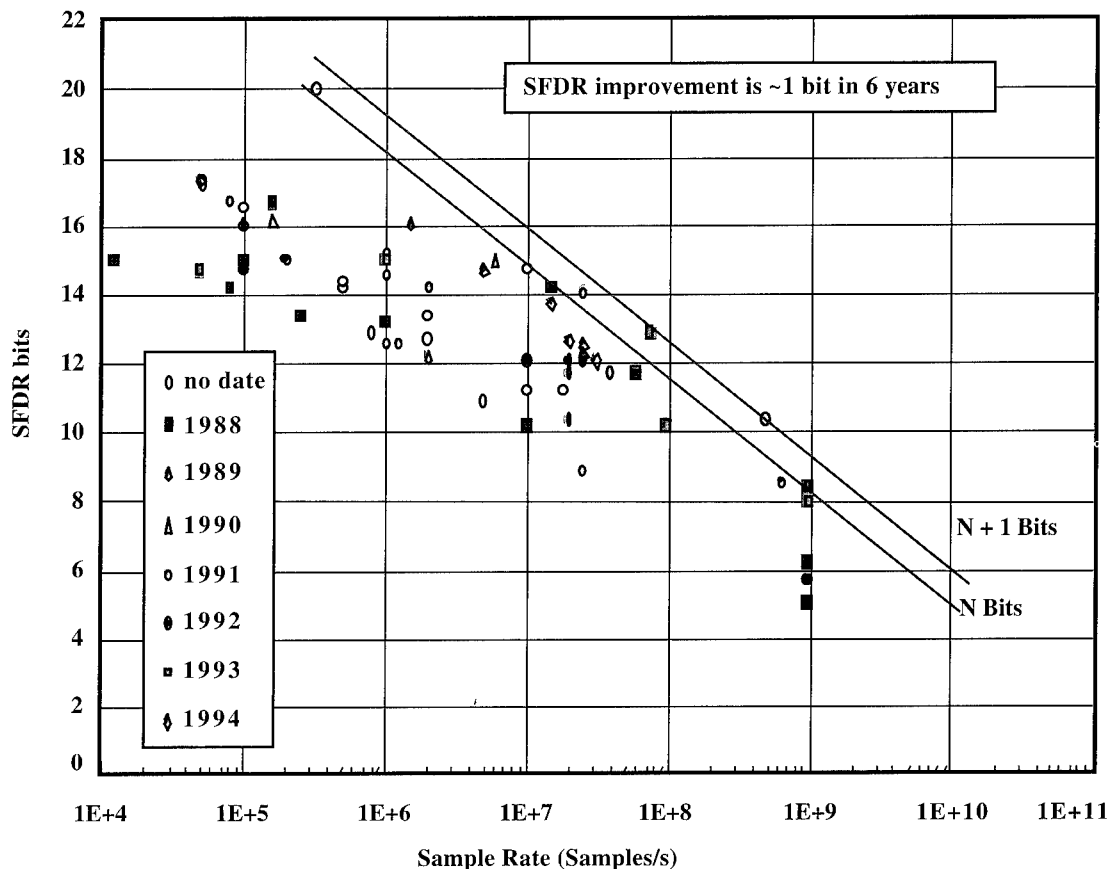
Figure 6-11. Time Development of A/D Converters With Respect to SFDR Bits

6.2.4 Enhanced and Affordable Sensing Through Signal Processing

The digital revolution has provided a common envelope of vast yet different forms of data and information providing an unprecedented ability to integrate, process and use disparate information. As stated earlier in Section 6.2.3, as A/D converters became more capable, the general trend in sensor systems is to move a sensors converter to the transducer and to eliminate more and more analog electronics. This trend toward early conversion from analog to digital signals has the effect of reducing the fraction of the system with historically increased costs while increasing the digital functions, thus allowing that part of the system to follow the declining cost curves of commercial digital processing technology.

Many of the advances in sensors that have been achieved recently and will be achieved in the future are directly related to concurrent and supporting improvements in two key areas: computer technology and signal processing algorithms. The exponential growth in computational capacity (ever increasing MIPS per pound, watt, and dollar) is well known. Also important for the advance of sensing systems, but less well publicized, are the dramatic innovations in signal

and data processing algorithms, for example, efficient large array image registration and two-dimensional Fourier transforms. By exploiting these two areas, it is possible to shift some of the burden from the sensor itself to the signal/data processor to achieve more affordable and/or enhanced overall sensing systems. This opportunity is often called "trading mass for MIPS" and generally involves using processing power to compensate for inadequacies in sensing hardware.

This section contains a set of representative sensor system concepts expected to be enabled, enhanced and/or made affordable through the availability of high performance computing resources. By no means are these examples meant to be exhaustive in either their concepts or coverage. They serve only to stimulate the reader to extrapolate to the many and diverse areas expected to provide the Air Force with next generation mission capabilities beyond those of today through enhanced sensors. Put another way, the benefits and enablements of digital technology will continue because the technology itself is still enormously fluid and, therefore, its impacts are difficult to predict but will definitely be varied and global.

Reduced Tolerance Sensing

The idea that adding processing power to an otherwise insufficient sensor can bring performance to acceptable levels within cost constraints is a fundamental theme for this section. A good example of this is the human vision system. The basic sensor—the eyeball—is fraught with imperfections and inadequacies. For example, the eyes of the human visual system collect 250 million pixels of information about 20 times per second. From this massive data stream, the tremendous processing power of the human brain turns these corrupted vision signals into sharp, usable images. Further, by processing two sensors simultaneously, the brain can render not only two-dimensional vision images, but full three-dimensional in full color!

An example of an important future sensor concept that illustrates this opportunity is "relaxed-optical-tolerance imaging." In the next several decades, the Air Force will have an increased need for fine resolution optical imaging of targets and scenes on a global basis. Using current technology, a space-based optical system with a large aperture would be very heavy to insure structural integrity and rigidity. It would also be expensive and cumbersome to fabricate and deploy. A solution to the current technology shortfall is to relax optical tolerances (thereby reducing weight) on the primary mirror and recover the loss with post detection processing. For example, the primary collector could be a non-rigid (floppy) monolithic or segmented or sparse device involving a very thin mylar surface stretched over skeleton structure. The large aberrations associated with this system would then be overcome with post-detection processing involving algorithms such as *phase-diverse speckle imaging* or *multiframe blind deconvolution*. These algorithms all involve a large number of computations that require on the order of tera-operations for a single million pixel image. The use of new algorithms and advancements in computer technology will allow the development of more affordable and improved imaging systems such as this.

Similarly, signal processing can provide the capability to exploit SAR image data from space or airborne platforms to detect and measure subtle changes in a scene between imaging passes. This technique is often called "coherent change detection" and involves using the phase differences between two SAR images taken with antennas that are displaced either spatially or temporally to retrieve information on motion, change, or surface elevation differences within

the images. Differences in phase are indicative of subtle changes between imaging cycles. For example, decorrelation in the image phase indicates changes have occurred in the scene microstructure due to surface disturbances such as might occur if a man walked across the scene. Small surface subsidences of a few mm due to clandestine underground activity can be detected using this sensing technique. These changes are usually not observable to a human viewing the scene nor can changes be seen in a conventional SAR image. This class of sensing techniques will have increasing utility in dealing with many operational tasks of interest to the Air Force in the future.

Ultimately, the goal of airborne and spaceborne imaging systems is to build up a model of the world so limited resources can be used in the most effective way. Typically, these systems are severely bottlenecked by their data rate and storage capacity. Evaluation of biological systems as a model for computer vision systems may offer some advantage or solution to add robustness and capacity to the current systems.

This is one aspect of affordability in sensing systems. Processing power can be traded for sensor precision—software algorithms can compensate for inadequacies in sensing hardware.

Review of Processing History

To further develop another concept of cost-performance improvement of sensing systems through enhanced signal and data processing and future algorithms and technology innovation, consider first the history of tactical sensing systems and then extend this history to future vision. Early tactical sensors used no computer processing. Radar and sonar operations, for example, involved state-of-the-art sensors that had direct analog connection to the mission operators. Tactical commanders observed the raw sensed data, drew conclusions about the military situation from these observations, and took action accordingly. The primary processor was the human brain—and it still is.

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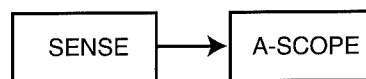
The introduction of digital computing enabled more usable display representations of sensed information by presenting the sensor outputs in tactical context. The commander's brain had a better connection to the sensor and more information to work with. For example, an airspace surveillance radar could produce historical *smoke trails* that showed where an enemy aircraft had been and, by extrapolation, where it was going. In addition, computer-generated background displays could show enemy and friendly airspace, and annotate radar reports with pertinent information.

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                 │ CONTEXT  │
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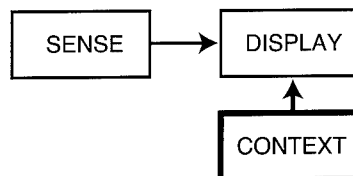
Increased processing power allowed the formation of *tracks*. More information could be extracted from the raw sensor reports by applying computer processing. In the tracking example, velocity data is extracted from position data.

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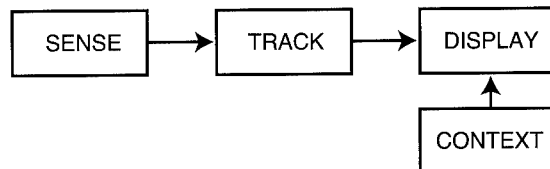
Signal Processing

Revolutionary progress was made when it became possible to digitize and process analog data at the rate it was produced. This is called real time signal processing, and it opened the door to vastly improved sensing performance while maintaining equivalent costs. A new processing step, called *detection*, was added to convert the raw analog inputs to usable sensing outputs.

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└─────────┘   └─────────┘   └─────────┘   └─────────┘
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                                         ┌─────────┐
                                         │ CONTEXT │
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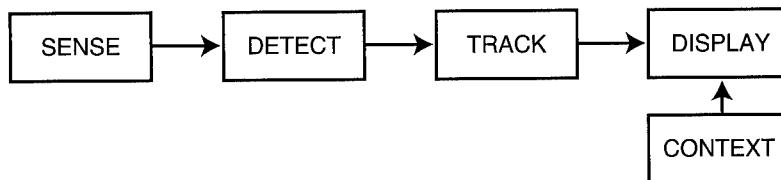
Modern signal processing algorithms for detection include fast Fourier transforms, matrix inversion, clutter suppression, image formation, jammer nulling, space-time adaptive processing and CFAR processing. In most all cases, the *sophistication* of the signal processing algorithm is limited by the available signal processing throughput. In fact, space time adaptive processing poses an (essentially) arbitrarily large problem in which detection performance is directly proportional to problem size. Detection performance can be increased solely by adding processing throughput to the signal processor. Figure 6-12 depicts the flow of a generic space time adaptive algorithm and notes appropriate division between special-purpose and general-purpose computing hardware.

Other techniques, besides expanding signal processor throughput, can improve detection. These involve feedback from the tracking algorithm (known as track-before-declare) and incorporation of contextual data in the signal processing (e.g., a geographic database can provide information about land-sea boundaries that can improve overall clutter suppression performance). Arguably, as will be discussed later, future algorithm development may well be as important to advancements in affordable sensor developments as improvements in hardware processors have been to date.

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                 ▲             ▲             ▲
        ┌────────────────────────────────────────┐
        │         CONTEXTUAL DATABASE            │
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BEST PERFORMED BY SPECIAL
PURPOSE PROCESSORS

BEST PERFORMED BY GERNERAL
PURPOSE PROCESSORS

RAW
RADAR
I/P

| EQUALIZE AND CALIBRATE | COMPRESS PULSE | FFT | NULL JAMMERS | NULL CLUTTER | DETECT TARGETS |

TARGET
DETECTION
O/P

100 to 1000 GFLOPS
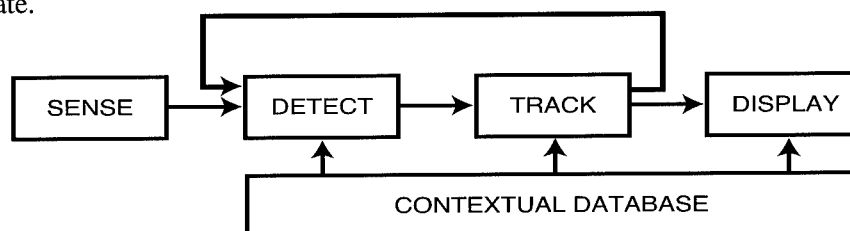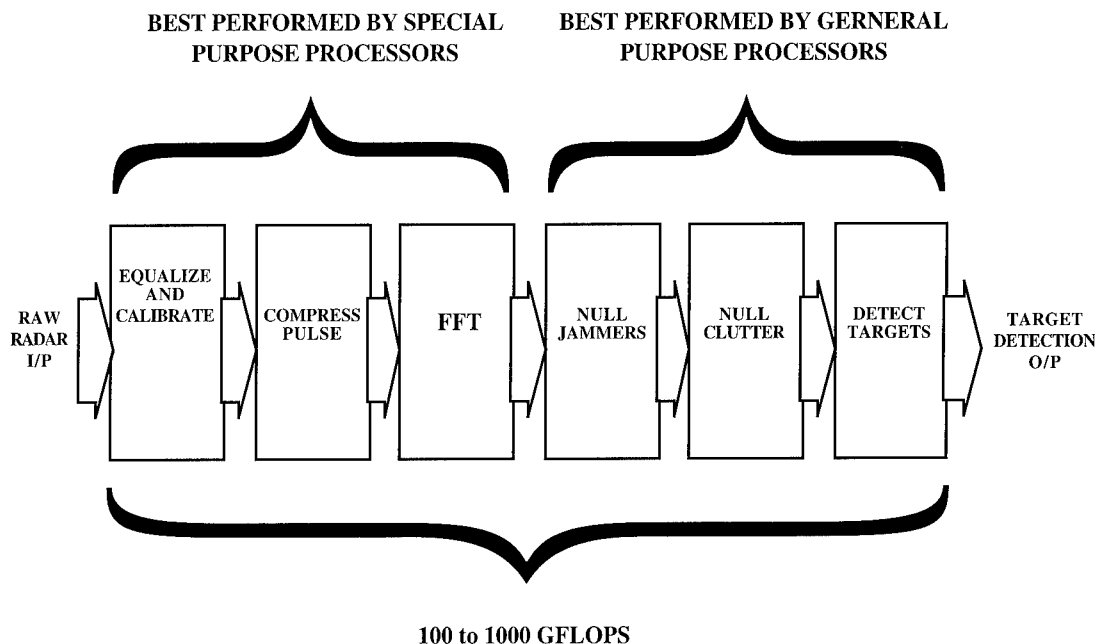
Figure 6-12. Generic Space Time Adaptive Processing Algorithm

State of the Art Sensing

Today we have digital sensors with adaptive and aided detection and context-based displays. Getting the tactical operator involved in the system by allowing real time control over the sensor reflects, at least approximately, the current state of the art in tactical sensing. Indeed, over a number of years avionics systems have been evolving toward more integrated and "open" architectures. Today's typical weapon system has integrated multifunction displays and controls and in some cases, such as the F-22 aircraft, a common processor for all sensor functions.

Future Vision

In addition to the improved cost-performance possible from increased signal processing, discussed above, future vision for sensing systems includes improvements that may be as revolutionary as that obtained from the innovation of digital signal processing. These additional technology innovations include wide area digital communications, improved processing algorithms, and methods for fusing and displaying sensed data.

Wide area digital communications makes it possible to connect multiple sensors together over large geographic regions. High performance computing can then fuse the individual sensing products into one, better, product. Data from *supplementary* sensors (i.e., sensors that are the same as, or similar to, the primary sensor) improves sensing accuracy by averaging noise and improving geometry. Data from *complementary* sensors (i.e., sensors that are basically different from the primary sensor) improves sensing utility by adding information that is otherwise unobtainable.

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The requirements are growing for more sophisticated physical/mathematical algorithms to more effectively interpret and fuse existing measurements. This indicates the need for *vigorous* development of application specific processing algorithms.

Fusion algorithms, like detection algorithms, are arithmetically intense. They include Kalman filters, multiple hypothesis trackers, optimization solutions and optimal association/correlation, plus many other algorithmic technologies heretofore unexplored because of lack of processing power. Fusion throughput estimates for an advanced radar system such as Joint STARS approach the 100 GFLOPS level, and next generation systems can easily be expected to require an order of magnitude throughput.

A key part of this concept is development of algorithms of "smart" resource managers that can adaptively allocate the apertures and "back-end" resources that will meet critical mission timelines. Control of the elements of Figure 6-13 from millisecond to minute time increments will be required for adequate control of most timeline requirements. Of particular importance are the limits of communication bandwidths that effectively define the amount of onboard processing and data compression that a given sensor system must provide to realistically be a *supplementary* or *complementary* element of such a "fused" system. For example, data compression based on not retransmitting images of huge areas where conditions are unchanged is certainly called for, and is being pursued quite vigorously in the commercial field for video phones, entertainment and the like.
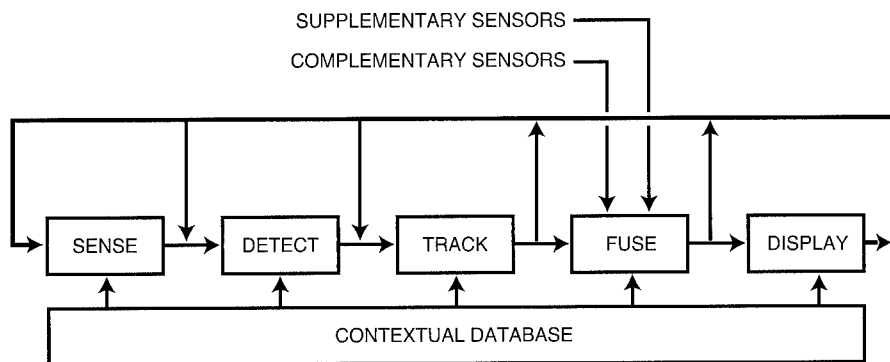
Figure 6-13. Future Sensing With External Sensors and Complex Interconnection

Another future sensing capability involves connecting the innate processing power of the human brain directly into the system. Virtual reality is only just beginning, but the possibilities for revolutionary improvement are apparent (Figure 6-14). The primary technology driver in this case is in algorithms for image generation—how sensor products can be rendered onto a display immersing the operator with complete situational awareness. Current technology supports two-dimensional imaging, while full three-dimensional virtual reality displays may be needed for realistic, next generation tactical applications.

As already discussed, a primary theme of this volume is that a complex system of systems is envisioned to operate over a military theater. As indicated in Figure 6-15, these systems include multiple sensors and multiple airborne and ground-based platforms. They will observe
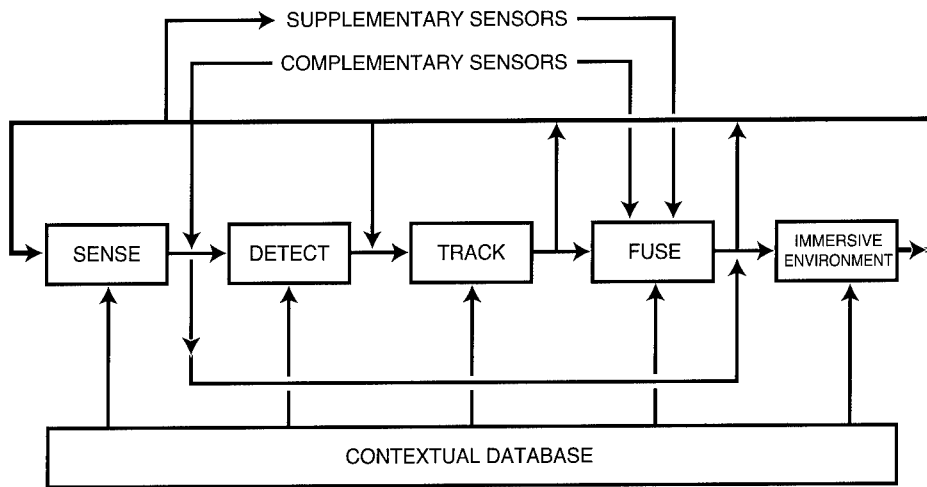
Figure 6-14. Sensing With Immersive Virtual Reality

and measure vast volumes of airspace and large areas on the earth's surface. Representative sensors and data sources shown in Figure 6-15 span the theater surveillance spectrum from air and ground targets to overall situation awareness.

SENSOR SYSTEM	PRIMARY SURVEILLANCE MEASUREMENT	PLATFORMS
AWACS		
AEW RADAR	AIRCRAFT/MISSILE SKIN TRACK	AIRCRAFT
GTR RADAR	AIRCRAFT/MISSILE SKIN TRACK	GROUND
IRST	AIRCRAFT/MISSILE 2-D TRACK	AIRCRAFT
IFF RADAR	AIRCRAFT BEACON ID & TRACK	AIR/GROUND
EIFF	AIRCRAFT ID & BEACON TRACK	AIRCRAFT
HRR RADAR	AIRCRAFT ID	AIRCRAFT
PASSIVE LOC	AIRCRAFT SKIN TRACK	AIRCRAFT
AIR TARGET ESM	AIRCRAFT ID & DF CUT	AIRCRAFT
FIGHTER AIRCRAFT	AIRBORNE TARGET BATTLE DAMAGE	AIRCRAFT
WEATHER	WX CELLS	COMMAND
CONTEXT DATABASE	GEOGRAPHY, DOCTRINE, PLANS	COMMAND
FRIENDLY FIRE	CORRIDOR/TIME/COORDINATION	ALL SOURCE
INTEL/AOB	AIR ORDER OF BATTLE	ALL SOURCE
INTEL/EOB	ELECTRONIC ORDER OF BATTLE	ALL SOURCE
INTEL/SOB	SURFACE ORDER OF BATTLE/FORCE STRUCTURE	ALL SOURCE
GROUND TARGET ESM	GROUND THREAT ID & LOCATION	SPACE/AIR/GROUND
ATTACK BOMBER	GROUND TARGET BATTLE DAMAGE	AIRCRAFT
DSP SATELLITE	MISSILE LAUNCH TIME & LOCATION	SPACECRAFT
SAR RADAR	GROUND IMAGERY	AIRCRAFT, UAV
E-O SENSOR	GROUND IMAGERY	AIRCRAFT, UAV
IMAGING IR	GROUND IMAGERY	AIRCRAFT, UAV
INTEL/TARGET	GROUND TARGET LOCATION & PRIORITY	ALL SOURCE/CMD
GMTI RADAR	GROUND TARGET MOVEMENT	AIRCRAFT
JSTARS		

Figure 6-15. Theater Surveillance Spectrum

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In the next sections are a few specific examples that illustrate the use of advanced processing to make high performance sensors more affordable.

6.2.4.1 Relaxed-Optical-Tolerance Imaging

Future Air Force Requirement

In the next several decades, the Air Force will have an increased need for fine-resolution optical imaging of targets and scenes of interest. Acquiring such imagery on demand for any place on the globe will be challenging but essential, given the increasing mobility of enemy threats and terrorists and the rapid pace with which events can unfold. The need for these capabilities suggests that a very large number of space-based optical platforms (providing global coverage), each having large aperture (providing fine-resolution imaging), will need to be designed and deployed.

Using current technology, a space-based optical platform with a large aperture would be very heavy to insure structural integrity and rigidity. It would also be cumbersome to deploy. Finally, fabrication of the large optical elements to optical tolerances would be a time-consuming effort. These factors make the design, building, and deployment of multiple platforms prohibitively expensive.

Technology Solution

A candidate solution to the current technology shortfall is to relax optical tolerances (thereby reducing weight) on the primary mirror(s) and recover the loss with post-detection processing. The driving principle is to "trade mass for megaflops." This is a favorable trade-off, given the cost/performance trends in computing technology. By allowing optical tolerances in the primary collector to be relaxed, we seek (1) a significant reduction in structural weight, (2) simplified deployment, and (3) reduced fabrication expense. There are many designs for the primary collector that could be considered. For example, the primary collector might be non-rigid (floppy), monolithic or segmented, filled or sparse. It could be a very thin mylar surface stretched over a skeleton structure that could be deployed like an umbrella. It may be important to design for a small compensating element conjugate to the primary collector to compensate for gross figure errors (larger than a wavelength) in the primary. Such compensation could be passive (fixed) or possibly active with a large dynamic range. Residual aberrations would then be overcome with post-detection processing. Algorithms such as *phase diverse spectral imaging* or multiframe blind deconvolution that uses multiple short-exposure (relative to changes in aberrations) images could be used to get optimal image reconstructions.

Current Status

Several advanced algorithms that perform post-detection correction of turbulence-induced blur have recently been developed. One such algorithm, called *phase diverse speckle imaging* has been used with great success to restore near diffraction-limited images of solar features in the presence of turbulence-induced aberrations. This algorithm requires that an in-focus (but blurred) and an out-of-focus image pair be collected for each of several aberration realizations. The algorithm converts the time series of image pairs into a near diffraction-limited image. The algorithm works extremely well in high-signal regimes, such as is encountered in ground-based

solar astronomy or space-based imaging of the earth. Special cameras are needed that can collect short exposure images and provide rapid readout with low noise. Such camera technology is rapidly developing for use as a component in wave-front sensors which in turn are used in adaptive optics. The phase-diverse speckle computations are dominated by two-dimensional fast Fourier transforms (FFTs). A refined reconstruction currently takes (conservatively) on the order of 1000 J FFTs, where J is the number of aberration realizations, and each two-dimensional FFT requires $\log_2 N^2 / \log_2 N$ floating-point operations, where N is the number of pixels on the side of an image. For N = 128 and J = 10, we require approximately $2.3(10)^9$ operations. A current single-processor Sun Sparc 20 workstation operates at about 40 MFLOPS so that a single reconstruction would take about a minute. The computations are highly parallelizable and special-purpose FFT chips could be employed to dramatically increase the computational speed.

Phase-diverse speckle is an example of an algorithm that could logically be developed and adapted for use in relaxed-optical-tolerance imaging, where fewer parameters might be needed to model the structurally induced aberrations.

Commercial Applications

Deploying a constellation of low-cost space-based optical platforms with the capability to perform fine-resolution imaging over the entire globe would have significant commercial and scientific value for use in natural-resource management, environmental studies, and ocean studies.

Impact on Affordability

The proposed technology is motivated by large savings in the cost of fabricating and deploying large primary mirrors in space.

Recommended Development Plan

The development of *relaxed-optical-tolerance imaging* technology requires a coordinated investigation of the kinds of time-varying aberrations that would be introduced with relaxed structural tolerances (by differential solar heating, mechanical vibrations, etc.) and the kinds of aberrations that can be accommodated while maintaining fine-resolution using post-detection processing. Once such aberrations are well defined, various system designs can be investigated, leading to a final design to be built and tested. Post-detection algorithms need to be further developed and adapted to the system concept. The speed of these algorithms can be increased to provide near real-time reconstructions. The development of small compensation elements with large dynamic range that actively correct gross aberrations needs to be investigated. There are also optical-design issues regarding compensation of gross aberrations that need to be resolved.

6.2.4.2 Thinned-Aperture Optical Receivers for Light-Weight Satellites

Technical Concept

One example of a sparse aperture for advanced, large-aperture, optical-reconnaissance satellites is illustrated in Figure 6-16. First, the receiving telescope aperture comprises three segments, thinned to approximately 10 percent of a fully filled aperture. Second, the telescope

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segments fold to a compact package for launch. Third, when deployed in space, the telescope optics are under active control to maintain alignment and image quality. Fourth, sophisticated image-restoration techniques are employed, so that the performance of the thinned receiver approaches that of a fully filled receiver.
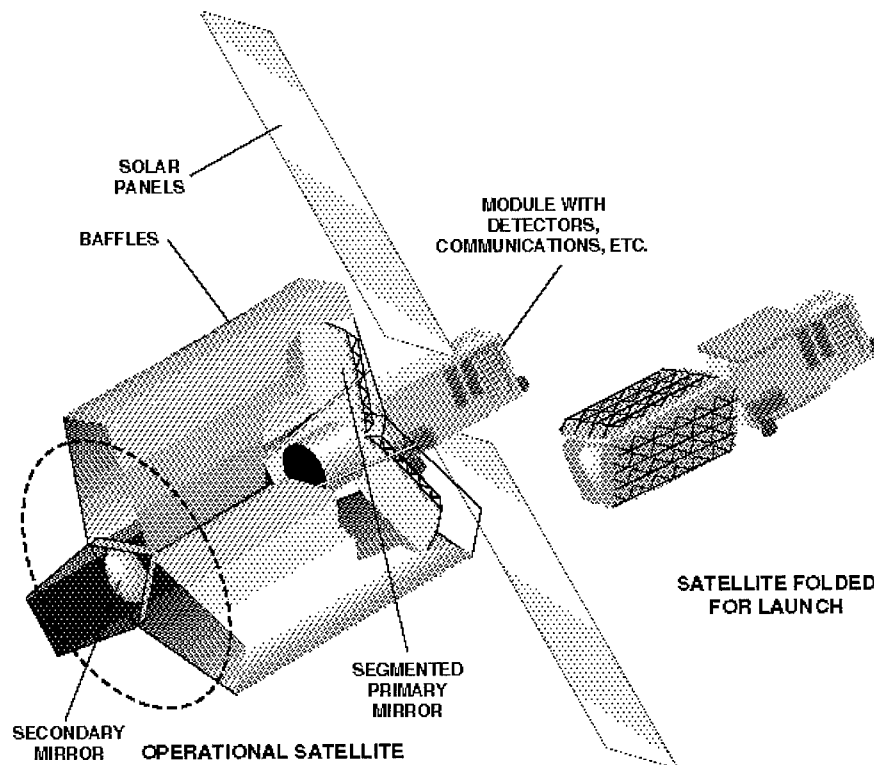
Figure 6-16. Thinned-Aperture Concept

Performance Analysis

Image-restoration algorithms have been developed to process data from a thinned aperture, and the performance has been analyzed using real satellite imagery. To provide a visual demonstration of the potential utility of a thinned-aperture system, a stressing case involving a collector having a fill ratio of only 10 percent was selected for analysis. The specific design is shown in Figure 6-17. Because such a large fraction of the collection area is removed, the high spatial frequencies collected by this system are heavily attenuated and must be restored in the image processing.

To test the image restoration, visible imagery collected by the LANDSAT satellite was used. Figure 6-18a shows the scene as viewed by the full circular aperture. The raw data from the thinned aperture defined by Figure 6-17 is given in 6-18b, which shows considerable smearing and evidence of a point spread function having six-fold symmetry. Partial restoration is achieved for an average signal-to-noise ratio of 10, as indicated in Figure 6-18c. Nearly perfect restoration is achievable at a signal-to-noise ratio of 100, which is graphically illustrated by Figure 6-18d.

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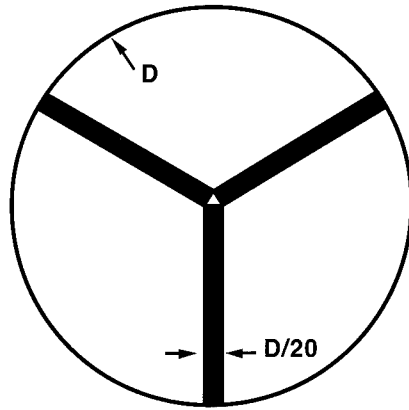
Figure 6-17. Illustration of a Three-Segment Thinned Aperture Having an Outer Diameter of D and Segments of Width D/20. The collection area of the design shown in this figure is approximately 10 percent of the full-aperture.
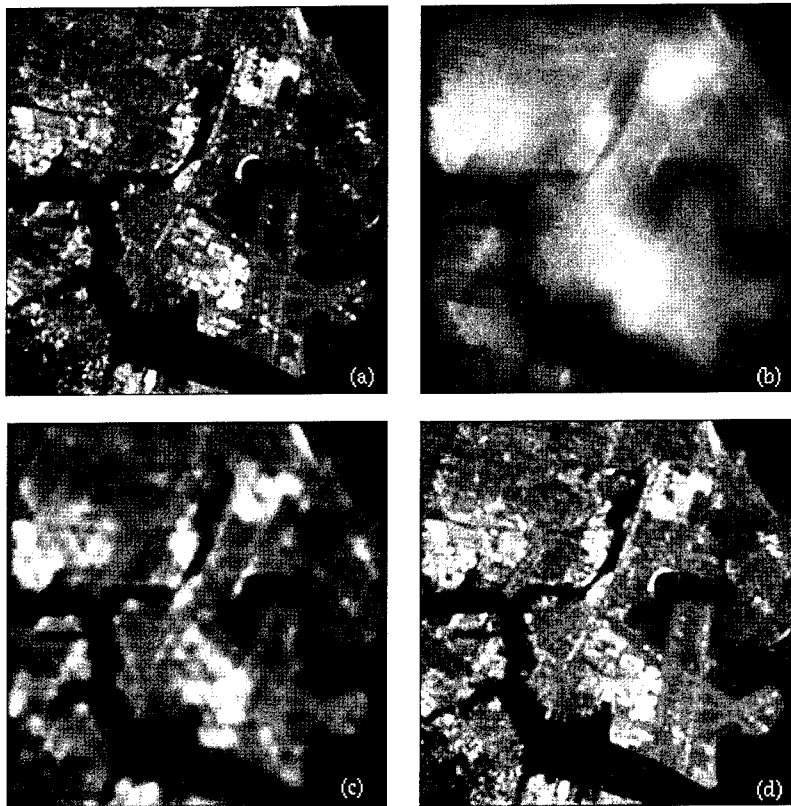
Figure 6-18. Comparison of Images Obtained From (a) a Diffraction-Limited Circular Aperture, (b) a Tri-Petal Receiver Having a 10 Percent Fill Factor, (c) Wiener Deconvolution for S/N=10, and (d) Wiener Deconvolution for S/N=100.

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Mission Applicability

This system concept is applicable to virtually all space-based optical reconnaissance, surveillance, and remote-sensing missions. It can be used for both infrared and visible wavelength sensors. It can also be used for active laser radar and LIDAR systems.

Because the concept permits high-altitude, high-resolution systems, it would be ideal for surveillance applications requiring continuous coverage. For instance, it could be used to provide a continuous situation-awareness picture of a battlefield or continuous surveillance of the manufacture, storage, and transfer of weapons of mass destruction.

The thinned-aperture concept is useful for systems to acquire, locate, and track air and ground targets. It can also be used for systems to perform space surveillance from space.

System Benefits

The thinned-aperture concept offers two significant advantages compared to conventional filled-aperture telescopes:

- It would have much lower weight (by perhaps a factor of 5) and a much lower launch volume.

- It can be scaled to very large apertures (i.e., tens of meters).

For any given aperture diameter (and thus resolution), the thinned-aperture concept will be able to use a smaller launch vehicle. Thus, there will be major cost benefits. Thinned apertures may also be made in sizes where it is inconceivable to fabricate or launch conventional telescopes. These very large apertures permit the construction of very high-altitude, high-resolution systems. Such systems can give continuous ground surveillance from relatively safe orbits.

The thinned aperture concept also offers benefits compared to a coherent array of telescopes, which is another method for achieving very large effective apertures in space. Thinned apertures do not have fundamental limitations on angular FOV, as do coherent arrays, and thus are superior for wide-area surveillance. In addition, the active alignment and phasing system is simpler for the thinned aperture than it is for coherent arrays.

Recommended Development Plan

The development plan for the thinned-aperture system should include the following elements:

- **Ground Demonstration Tests.** These tests would demonstrate the critical functions of unfolding the primary-mirror segments, deploying the secondary mirror, controlling the figure of the primary-mirror segments, and phasing the mirror segments to form a coherent image. The ground tests would start at modest size (~2 m) and scale up to greater than 10 m.

- **Detailed Conceptual Design.** It would be helpful to do a detailed conceptual design for a far-term application—perhaps for a high-altitude, tactical reconnaissance system. Such a design would help guide the technology development.

- **Near-Term Space Demonstration**. This test would demonstrate the thinned aperture concept at a small scale (perhaps 1 to 2 m). Such a demonstration could be done as a low-altitude, small satellite package.

6.2.4.3 Space-Time Adaptive Processing

Airborne radars must deal with interference in their sidelobes that can obscure the desired targets. Two kinds of interference are prominent. Returns from the ground enter through the sidelobes as clutter; unlike sidelobe clutter in a ground based radar, this clutter has a nonzero Doppler shift as a result of the relative motion of the radar and the ground. Jammers can also get energy into an airborne radar through the sidelobes. There are a number of techniques available to mitigate this interference. The most straightforward approach is to build an antenna with low sidelobes; this approach is used, for example, by the E-3A. However, this can be very difficult, as it requires very careful consideration of the antenna, radome and aircraft interactions. These difficulties make this approach very expensive and limit the practical sidelobe levels. With an array antenna, better performance against jammers can usually be obtained at lower cost using adaptive nulling; that is, by choosing the weights of the elements, in real-time, to put a null in the antenna pattern in the direction of the jamming signal. This has been deployed for GPS receivers and communication systems. A simple version, sidelobe cancellers, is in fairly common use on surface based radars.

Adaptive nulling needs to be modified for sidelobe clutter, which comes from all aspects. The Doppler shift of any piece of clutter depends on the angle between the velocity of the platform and the vector between the platform and patch of ground. Thus, if one can choose element weights independently for each Doppler filter, one could null out the sidelobe clutter that contributes to that filter. This is called space-time adaptive processing (STAP). To implement STAP requires a receiver for each element and extensive processing power. Modern computer technology makes the processing possible. The advent of sufficiently fast A/D converters to allow an all-digital receiver will make it possible to fit a STAP system in smaller and cheaper packages.

STAP has application to any airborne radar. It is of particular value to radars that are looking for low flying, low radar cross section targets such as cruise missiles. If an adaptive nulling or STAP system could be fit into a missile, it would have great benefit in defeating monopulse endgame countermeasures such as towed decoys and ground bounce jammers. In addition to allowing improved performance at lower cost than conventional low sidelobe antenna designs, adaptive techniques can allow the use of antennas that would otherwise have unacceptable patterns but may be desirable for other reason, such as reduced RCS.

There are a number of other signal processing ideas and applications that rely on ideas similar to STAP. For example, a synthetic aperture radar usually forms a beam that is focused for a particular target velocity, usually zero. With post-detection processing, simultaneous SAR beams can be made, each one focused for a different velocity.

To date, STAP has not been deployed in any fielded system, but there have been field test programs, so this technology should be ready for a development program. This technology must be considered seriously for next generation airborne radar systems.

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6.2.4.4 Advanced Airborne MTI

Introduction

As another example of enhanced sensing through signal processing, we discuss advanced airborne MTI radar systems in this section.

MTI systems are important to the military since most targets of interest are in motion at one time or another. Many targets are most vulnerable or pose the least threat when in motion. Many targets are often well hidden when not in motion. Moving targets are hard to conceal/camouflage. Motion of a target is a strong indicator that it is still functional and has not been disabled. From a low intensity conflict perspective, tracking specific vehicles in traffic provides information related to drug trafficking, NBC weapons production and capability, and terrorist movements. The ability to detect/classify these targets in this scenario is, therefore, operationally very important.

MTI systems provide ideal applications to demonstrate and exploit the technological developments in high performance computing. Real-time radar signal processing requirements stretch a digital system's input speed and bandwidth, and the various MTI algorithms (both detection and exploitation) create a requirements pull for scaleable software engineering. MTI sensors benefit through product improvement in radar processing and packaging, as well as through a technology push for backend exploitation of sensor products.

MTI radars are sensors optimized to reject signals from fixed or slowly-moving, unwanted ground clutter such as buildings, terrain and precipitation while retaining for detection and display returns from moving targets. Targets move when they want, not necessarily when it is convenient for a sensor to see. Consequently, day/night, all weather capability is required to find and track moving targets. This motivates the use of radar based MTI systems as opposed to EO systems. As a principal sensing element of an air-to-surface search radar or airborne battlefield surveillance/management system, MTI radars will continue to evolve from their current modes, performances, sensitivities and discrimination capabilities as driven by overall system operational concepts and performance requirements of future Air Force missions. (See Figure 6-19.)

The MTI elements described by this section will more likely require mainly *evolutionary* advancement in sensor and platform implementations. However, system architectures described earlier in this document will show significant potential in effecting *revolutionary* advancement in mission capabilities. Performance gains are expected to be brought about by:

- Projected advancements in computational throughput

- Real-time sensor product creation, fusion and exploitation

- Collocation (in a theater sense) of a wide variety of sensor types

- Automated cross-cueing for on-board and external sensors

Data Rates and Volume

As an element of an integrated "system of systems" in support of the operational tasks described in Section 4, MTI sensors will be required to survey ever larger areas of interests (AOIs) at increasingly higher revisit rates and resolutions. Typical examples of these requirements

might be to survey an Army Corps area of some 40,000 km^2 AOI every 5 to 10 secs at resolutions of 5 to 10 meters. These numbers drive sensor output data rates and signal processing requirements to an order of magnitude beyond today's current capabilities.

Deep-Look Surveillance with/without Overflight

- Detection, Tracking, Targeting
- Classification Tracked vs. Wheeled
- Realtime Targeting to Decision Makers
- Attack Results
- Onboard Processing and C2

Multi-mode Radar
- Moving Target Indicator (MTI)
  - Wide Area Surveillance (WAS)
  - Sector Search (hi-res, rapid revisit)
- Synthetic Aperture Radar (SAR)
  - Photo-like Imagery
  - Fixed Target Indicator (FTI)

- Tanks
- Trucks
- Ships
- Trains
- Helicopters
- Rotating Antennas
- Low/slow Aircraft

Figure 6-19. Nominal MTI System

Improved Sensor Performance

To meet the demanding operational requirements leading to the above mentioned data rates and volumes, *nominal* performance gains in sensor A/D technology, affordable high power T/R modules and adaptive multichannel antennas will need to be developed. Auto calibration techniques should allow for utilization of lower performance but fully characterized array elements such that sensor level integration of these elements compensates, at a system level, for component level limitations. For example, full system level adaptive processing techniques to include calibration techniques to control antenna sidelobe level, jammer nulling and sidelobe cancellation could significantly reduce the cost for next generation antennas.

Many of the major challenges in moving target imaging can be circumvented by some enabling technologies. Some of the technologies are very straightforward and others somewhat subtle:

- **Faster Platforms**. This provides the ability to synthesize large apertures for fine resolution or multispectral collections quickly. This mitigates the smearing of the signature and reduces the amount of refocusing that must be applied.

- **Single Transmit—Multireceive Platforms**. This is another approach to Faster Platforms mentioned above. With multiple receive platforms, the aperture can be synthesized more quickly and provide finer resolution with less motion smearing.

- **Dynamically Changing PRF**. This provides two benefits. The first is that the PRF would change according to a perceived target motion during collection. This serves to provide a constant sampling rate over the collection aperture which minimizes IPR distortion in the focused target. In addition, this feedback may provide a means to actually change the platform velocity vector to enable the finest possible resolution in the least amount of time.

- **Phase History Based Algorithms**. Applying the focusing algorithm directly to the SAR phase history as opposed to first forming a defocused image has a number of advantages. The first is that sophisticated time series models can be used to predict the target motion, which would help in focusing. The second is that it may be more robust to apply the ATR algorithms directly in the phase history domain and not bother refocusing the signatures.

- **Coded Waveforms**. If there is some prior knowledge regarding the specific target motion (e.g., it will be going through a specific bend in a specific road), the transmission waveform may be coded such that the target of interest is maximally separated from the competing clutter. This would be especially useful in tracking where the target type is already known. The waveform can then be designed for that particular target signature and expected motion.

One advantage of improving MTI radar systems to include SAR based mechanisms for imaging moving targets is the leverage gained with improved and advanced processing for basic SAR image formation. Specifically, in recent years there have been great advances in linear and nonlinear spectral estimation techniques. The techniques have shown promise to provide increased mainbeam resolution, reduced sidelobe levels, and clutter discrimination in a wide variety of radar applications. The algorithms also have the characteristics of being very computer intensive. With the advances of computer technology, the algorithms are soon to be practically implementable for operationally interesting image sizes.

Improved Asset Management

Figure 6-20 is an example of today's MTI system operating over a Corps area. Indicated are a multitude of MTI radar modes to support mission objectives. However, most of today's current MTI modes are driven by resolution and revisit rates where a next generation should eliminate this need by supplying full sensor capability over the entire wide area **simultaneously**. This then enables target track and enhanced target discrimination on all targets.

Elimination of currently redundant MTI radar modes makes possible the scheduling of sensor resources for new and innovative MTI modes such as terrestrial inverse SAR (the imaging of many moving vehicles), enhanced helicopter and slow flying aircraft identification. These new MTI techniques are driven by time-on-target and SNR requirements for development of discrimination signatures, time that is viable only with improved asset management.

WAS: Wide Area Surveillance
   • Very large area (space coverage)
   • History replay (time coverage)

SS: Sector Search
   • High/med/low resolution

AP/AC: Attack Planning Control
   • Small area
   • High revisit rate

SAR: Imagery
   • Terrain/targets
   • Fixed size/resolution
   • Mosaic option

Corps Area: Nominal 200 km x 200 km
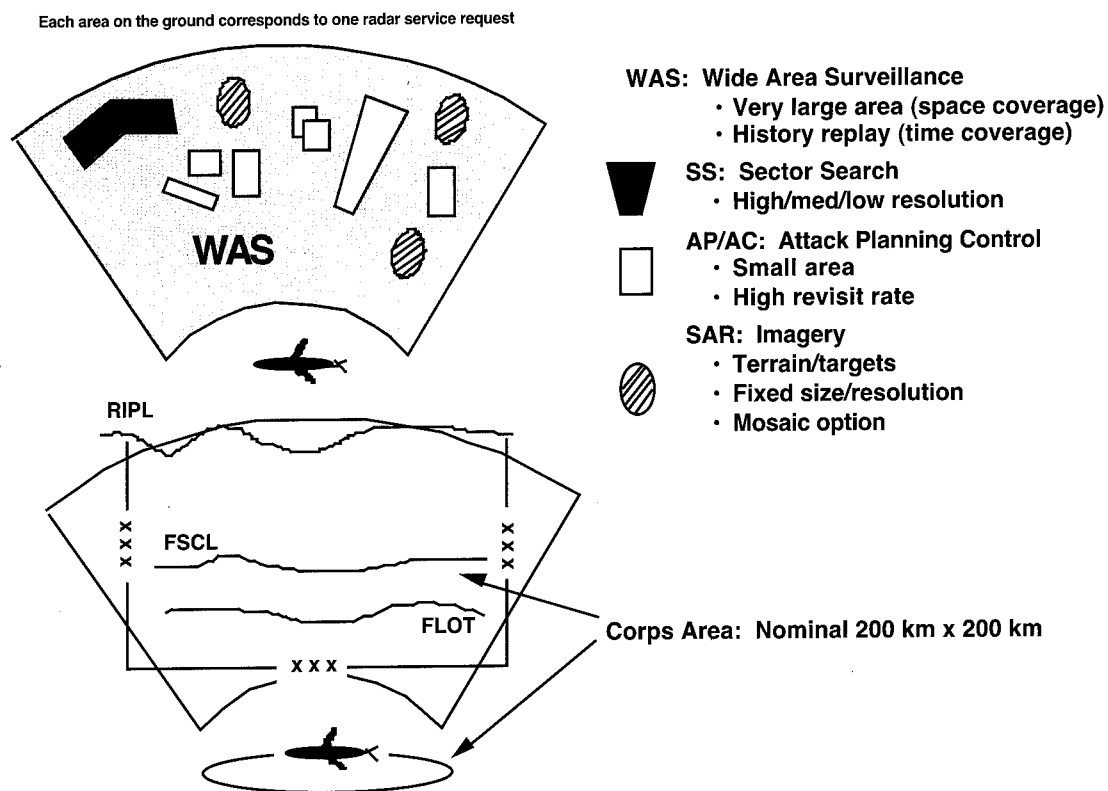
Figure 6-20. Notional MTI System Operation Over Corps Area

The major challenges in detecting/classifying moving targets stem from the size of the targets of interest and the many competing moving objects that may be in the same scene. Previous successes in the refocusing of moving objects have been with large targets. Currently, there is a large amount of research in exploiting fine resolution SAR data to detect and refocus the moving target such that ATR algorithms can be applied for classification. The challenges are:

- Smaller targets motivate finer resolution systems. In SAR, this translates into longer dwell times. Even though the target motion itself can translate into finer resolution through enhanced rotation, there is no control over target motion so there is no guarantee of enhanced resolution.

- Competing moving objects may defocus onto the energy of the target of interest. This added clutter will contaminate the target signature and degrade performance of the focusing and ATR algorithms.

- Focusing algorithms require prominent points to track motion and focus. Performance is degraded by low target-to-clutter ratio either via target signature reduction or high competing clutter.

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- The timing of the moving object being in the collection beam of the SAR is tenuous. SAR beamwidths are not so large as to guarantee that a cued moving target will be in the beam.

- The ATR algorithm suite needs to be redesigned since the targets will not be refocused perfectly and the target motion actually changes the sidelobe structure of the SAR IPR. Classic template matching or model based vision algorithms may need to be completely redesigned.

Additional enhancements are summarized for MTI sensors in Table 6-4.

Table 6-4. Sensor Technologies Specifically Applicable to MTI Radars

Technology	Operational Benefit	Area of Improvement Required

Higher degree of dimensionality	Improved Target Discrimination	• Wider operating and instantaneous bandwidth supporting combat ID
		• Range resolution improvements by a factor of 5-10
		• Improved ECCM capability
		• Higher PRFs for signature development of:
		  helicopter classification
		  tracked/wheeled
		• Additional MTI radar modes:
		  terrestrial inverse SAR
		  maritime inverse SAR
		• 2-D active electronically scanned antenna (ESA)

	Enhanced Countermeasure Resistance	• Higher SNR allows smaller target features to be observed • Improved target location accuracy

Adaptive behavior	Enhanced Clutter Rejection & Countermeasure Resistance	• Massively parallel signal and data processing:
		  full STAP
		  5-10x wide area surveillance update rate
		• Simultaneous MTI and SAR data collection
		• Non-conventional signal processing management
		• Improved ECCM/EMI
		• Expanded bandwidth
		• Adaptive beam processing
		• Automatic sensor resource management
		• Auto track of any MTI

	Enhanced Operator-System Interaction	• Automatic system health and reconfiguration • Operator interfaces and control

Data fusion	Enhanced Target Detection/ Classification/Identification Redundancy in Critical Functions	• Additional radar modes
		  high resolution large swath SAR
		  interferometric SAR ATR Elements
		  object identification
		  change detection
		• Area Delimination
		• Smart scheduling

Development Status of Advanced Airborne MTI

Despite a continuing need to observe *real-time movement* of ground forces on the battlefield at extended ranges, this capability did not exist for wide area coverages until very recently, with

development of the U.S. Air Force/U.S. Army system, Joint STARS and for smaller area coverage with helicopter-borne systems like the French HORIZON and Italian CRESO.

While the physics of moving target radar surveillance has been well understood and employed on less sophisticated systems for many years, the technology needed to provide the signal and data processing capacity for wide area surveillance and the detection of slow moving ground and low flying airborne targets has become available only within the last decade. In the early 1980s, the Air Force's PAVE MOVER and Army SOSTAS programs demonstrated conclusively the combined power of emerging digital processing technology and sophisticated radar processing algorithms to detect slow moving targets. As an outgrowth of this program, in 1985 U.S. development was beginning on the Joint STARS featuring a powerful multimode ground surveillance radar system and sophisticated command, control and battle management capabilities installed in a militarized Boeing 707 aircraft. In less than 5 years, the Air Force, the Army and OSD (recognizing the immense potential value of this MTI system) extracted the Joint STARS system from development and deployed it to the Persian Gulf for Operation Desert Shield/Storm

The technologies needed to field an order of magnitude improvement in MTI radar sensors in the next 20 years are near or on the horizon. Specifically, processing technologies will continue to derive benefits from commercial developments and, therefore, enhanced radar algorithms for deriving maximum performance from collected RF should continue at a rapid pace.

Elements of the sensor proper associated with the antenna will continue to be driven by the need for low cost, high performance T/R modules and subarrays as well as the RF electronics. Support of continuing efforts in the technological development of these components will be necessary to insure low cost sensors for the future.

Research into additional ground clutter phenomenology needed for development of enhanced algorithms for even higher levels of space-time-adaptive processing must also continue. As digital processors provide near limitless capacities, newer and more sophisticated detection and identification algorithms need to be developed.

6.2.5 Automatic Target Recognition (ATR)

Introduction

The capability to reliably and automatically recognize sensed visual, IR, and radar images or electronic signatures will provide significant operational benefits to the Air Force in mission areas requiring rapid target identification, intelligence data analysis, and battle damage assessment. The state of the art of (spatial) pattern recognition does not yet provide sufficient accuracy or reliability to perform independent and unambiguous ATR for lethal attack in all mission applications, but it does provide the ability for rapid screening and cueing to support the warfighter.

Current commercial technologies in spatial modeling, geospatial information systems and automated reasoning are being leveraged to support model-based vision developments to expand the performance envelope of commercial pattern recognition systems. We recommend that the Air Force: (1) Expand the model-based technology developments for imagery to include full hybrid ATR including all-source context, (2) Expand and coordinate technology developments

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to extend model-based reasoning to multiple-sensor applications, and (3) Leverage commercial neural network, image understanding and spatial database technologies to augment model-based ATR with additional contextual data

6.2.5.1 Pattern Recognition Technology Description

Pattern recognition technology provides the capability to automatically discriminate objects or events in visual (2-D or 3-D) imagery, IR and radar imagery or non-image (e.g., SIGINT or acoustic) sensed data. Pattern recognition has applications in military intelligence, security, targeting, real-time target identification, industrial robotics and medical diagnosis. In Air Force mission applications, pattern recognition technology is most often applied to ATR problems.

Technology Description

We can illustrate the general ATR process by describing the application for detecting, locating and targeting objects from surveillance imagery. The ATR process includes a portion or all of the following cascaded stages, each of which performs a pattern recognition function:

- Detection/Bulk Filtering rapidly eliminates uninteresting areas in the surveillance data from further consideration, leaving regions of interest (ROIs) which exhibit target- like properties with respect to the features used for detection/bulk filtering.

- False Alarm Discrimination further removes from consideration those ROIs that are "non target like," with respect to a more detailed and context-dependent set of features.

- Classification/Indexing associates a given ROI with one or more likely target classes (eliminates highly unlikely target classes from consideration).

- Recognition identifies specific type of object within a given class.

In general, the level of processing complexity increases with the progression from detection/ bulk filtering through recognition. Detection/bulk filtering must process wide geographic areas and is typically implemented using wide area sensors (search resolution SAR), very high speed relatively simple processing algorithms (CFAR, spatial morphology, area delimitation based upon terrain classification, etc.), and features that are independent of specific target attributes (amplitude, polarimetric features, size, etc.). The latter three stages process localized areas and may exploit higher resolution limited FOV sensors (IR, laser radar, ultra high resolution SAR), more demanding algorithms (neural nets, and model-based reasoning), and more target-specific features (texture, fractal dimension, and localized image signature attributes).

Development Status

The preponderance of current research effort in ATR has focused on detection/bulk filtering and false alarm discrimination. Applications of these processes have been successfully demonstrated against medium resolution (1 meter) SAR imagery using two-parameter CFAR, morphology-enhanced CFAR algorithms, and features such as shape descriptor, size, polarimetric purity, and texture measures such as fractal dimension.

While the most stringent criteria for residual false alarm rate (0.01 false alarms/km^2) in autonomous mode have not yet been achieved over all types of terrain, this technology is well in

hand for large targets in the open, in low clutter regions. Heavy clutter and targets in "hide" conditions (deployed with CC&D, beneath heavy foliage, adjacent to urban structures, under bridges, etc.) still pose serious challenges to both ATR and sensor technologies. The performance goals and throughput requirements for autonomous detection/bulk filtering operations (medium and large targets in low to moderate clutter with limited CC&D) will be achieved by the end of the decade as techniques for area delimitation are improved and are more tightly coupled with the data processing algorithms and as special-purpose processors mature. Significant utility has already been demonstrated to support analyst cueing for wide area search target detection in a number of programs.

Target classification and recognition are somewhat less mature for two reasons. First, the dimensionality of the problem is significantly greater than for detection/bulk filtering, requiring much more sophisticated algorithms. Second, it is being realized that the use of multiple sensor dimensions offers a key advantage to, and may even be required for, robust target recognition across many scenarios. (Increased sensor dimensionality is discussed in Section 6.2.8.) Specific rigorous research on the selection and use of multiple sensors for target recognition has been slow to happen. The performance of classification and recognition processes is both target and clutter dependent. In addition, efforts to perform reliable automated recognition are confounded by increasingly sophisticated forms of CC&D.

Classification/recognition algorithms all operate by matching attributes of the measured (unknown) signature with *a priori* information about the potential targets that could be present in the scene. Algorithm technologies differ in terms of the type of information used to match, the way in which the *a priori* information is encoded, and the approach used for matching. The matching algorithm technologies which have been the focus of classification/recognition research fall into four broad categories:

- **Statistical Pattern Recognition**. Partitions the space of possible target identities according to how target signature attributes can be partitioned.

- **Neural Nets**. Models the information flow across components in the human brain to perform the reasoning process that matches pre-stored target features against the unknown to identify it.

- **Template Matching**. Codifies the topological structure of the target signatures for all possible unknowns from *a priori* data and matches this against the unknown signature to select its most likely identity.

- **Vision**. Applies reasoning based on incremental signature correspondence between the unknown and the signature properties of all feasible targets to determine the most likely identity of the unknown.

The bulk of the ATR algorithm research to date has focused on statistical pattern recognition (SPR), largely because it draws, in a relatively straightforward way, on well established research in estimation theory. The remaining three matching functions (neural networks, template matching and vision) have recently received increased attention to overcome some of the limitations of SPR that arise from the fact that target signature features seldom conform to the statistical distribution assumptions that must be made to support decision metrics.

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The technology roadmap of ATR technology, applicable to ground target surveillance, is summarized in Figure 6-21 showing several legacy developmental systems and the key technologies that formed the basis of those capabilities. The Air Force successfully transitioned statistical pattern recognition to radar non-cooperative recognition applications (e.g., Dual Mode Recognizer) in the 1980s, but these techniques, alone, have not proved sufficient to solve image-based problems.

Three Decades of ATR Algorithm, Processor Technology Development

1970s	1980s	1990s	Future

Air Force Operational — UAV SAR

Development — LANTIRN — DMR NCTR — Strategic Imagery ATR — SAR/EO ATR

Research — Multi-sensor ATR — Statistical ATR, Low-level Feature Extraction — Hybrid Model-Based ATR — Mission-Based, Model-Driven ATR — Contextual Adaptive Mission-Based — High-level KBS — Neural Net ATR

State of the Art			
Statistical ATR	Context-based Statistical and Syntactic ATR		Model-based Multisensor ATD/C Detailed Target Modeling

Performance			
Appealing	Promising	Feasible	Introduction

Figure 6-21. ATR Technology Roadmap (for Image-Based SAR and IR/EO Applications—Ilustrates the Move From Statistical Pattern Recognition Approaches to More Complex Vision Systems That Apply Mission Context Data

In this decade, the transition to *model-based techniques*, supported *by mission-based information* (e.g., precision map and terrain data, real-time fused intelligence data supplying accurate context) will provide ATR system performance improvements at the same time sensor resolutions are increasing, and multiple sensor data sources will provide greater observable dimensionality to discriminate targets. The matching technologies can be supported by *a priori* target characterizations that are data driven, model-based, or employ a combination of both.

Data-driven techniques characterize the signature attributes of the target based upon extensive processing of representative real signature samples (training). While these techniques

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capture all of the inherent properties of real data signatures, matching strategies that employ them fail or are severely degraded if the unknown signature does not conform to the target configuration or acquisition conditions embodied in the training data.

Model-based techniques codify the *a priori* information about unknown targets using an explicit model of the target geometry, coupled with a sensor model that transforms the target geometry into signature attributes. Model-based target characterization has the advantage that signature attribute predictions can be directly tailored on line to the specific conditions under which the unknown target signature was collected (observed), and thus can adapt real data that may not have been collected previously. The performance of model-based techniques, however, is critically dependent on the fidelity of the target geometry and sensor models in terms of predicting the expected signature attributes for matching. With the advent of improved techniques for target modeling and with higher fidelity and faster sensor models, the focus of recent research is shifting to the use of model-based techniques for target characterization.

The current state of the art in classification/recognition employs model-based techniques for target characterization, coupled with either vision-based reasoning or neural net based algorithms to support the matching function. While significant progress has recently been made in classification/recognition algorithms, the technology is not sufficiently mature in terms of performance, throughput, or miniaturization to support autonomous operation against a broad class of targets. However, the feasibility of the technologies has been demonstrated against sample real data target sets over a range of acquisition conditions. One near term application in which the technology should be pursued is its use in man-in-the-loop applications to support image analyst throughput improvement.

The current state of the art can be summarized in terms of the minimum research thrusts being performed:

- Detecting/identifying target groups (ships at sea, missile launch battalions)
  - Currently in development
- Detecting/identifying large targets in the open (port monitoring, airfield monitoring)
  - Cueing tools robust
  - Recognition possible with modest resolution
- Detecting/identifying small targets in the open (tanks, scuds)
  - Cueing tools robust
  - Recognition requires time resolution or polarimetry
- Detecting/identifying target in hide (tanks in trees)
  - Modest success with cueing; needs more testing
  - New advances in sensor technology
  - Advancements needed in recognition algorithm technology

- Detecting/identifying moving targets in low clutter
  - Cueing techniques in advanced development
  - Identification based on radar signal modulation or one-dimensional/two-dimensional images shows some promise
- Detecting/identifying moving targets in strong clutter
  - Initial results encouraging; needs more testing
  - Needs development of recognition technology

In summary, ATR technology has had modest success across a spectrum of applications. The most successful application has been to aid the human analyst. The simple and direct problems in the hierarchy above are certain to receive significant gains from this technology. With the advent of improved observables, the use of ATR technology will quickly come to maturity.

6.2.5.2 Relationship to Key Air Force Missions

Pattern recognition technology is applied to automatic target recognition in numerous application areas that require rapid searching of large volumes of data, sorting of events and objects, and accurate identification of those events and objects.

Specific Applications

A wide range of Air Force mission areas, identified in Table 6-5 currently apply or are candidates to apply ATR in the future. The table summarizes the applications and potential enhancements that may be provided by ATR.

The contributions of pattern recognition, across all applications, can be grouped into one of four areas:

- **Capability to Support Expanding Imagery Workloads.** ATR will provide the critical capability to screen (detect) and ultimately classify/identify targets in the ever expanding volume of image data that is becoming available to Air Force warfighters. Unmanned Air Vehicles (e.g., Tier 2+, 3-), commercial satellite sensors and GIS data sources will provide a deluge of data that must be automatically screened and processed.

- **Improved Detection/Identification Accuracy.** ATR provides the potential to use all available elements of information to achieve higher detection performance (higher P_d, at a given P_{fa}) than achievable by human operators only.

- **Improved Detection/Identification Speed.** ATR also provides speed enhancements over aided (semi-automatic) or manual analytic recognition approaches.

- **Reduced Warfighter Workload.** ATR reduces the workload for pilots, intelligence analysts, planners, and commanders, allowing them to focus on higher-level tactics rather than information screening.

Table 6-5. Air Force Representative Operational Tasks and Related ATR Applications

Operational Tasks	ATR Application(s)	Enhancements Provided by ATR
1. Real-Time Situation Awareness	Target identification Threat assessment Intent recognition	Reduction in manual recognition activities necessary to assess high-level situational patterns
2. Global NBC Capability Surveillance	Facility, equipment, and materials detection	Wide area screening for potential NBC activities Accurate detection of NBC materials, equipment and facilities
3. Hardened/Underground Facility Surveillance	Facility detection and related activity monitoring (change detection, process activity)	Wide area screening for facilities development Focused area monitoring for facility operations
4. Recon and Deliver Weapons to Air-Ground Targets	Non-cooperative air and ground target identification Autonomous seeker target detection and ID	Reliable, lethal detection and identification of lethal targets
5. Detect, Track, Intercept Theater Ballistic Missiles	Missile typing via ground, air, space sensors	Improved speed to recognition and accuracy of type ID
6. Acquire, Maintain, Disseminate Info for MOOTW	Identification of non-military or clandestine vehicles, equipment and materiel	Reliable screening, detection and classification
7. Force Sustainment and Product Assurance	Non-destructive analysis Facial, retinal recognition for security	Rapid, accurate identification of material characteristics, personnel

6.2.5.3 Commercial Developments/Applications

There exist a number of commercial activities that are developing and applying pattern recognition-related technologies that may have leverage potential to support Air Force activities in this area. In two areas, the Air Force should consider evaluation and application of available COTS technology.

Short-Range Industrial Pattern Recognition

Several commercial areas that are providing complementary ATR technology for lower-volume, pattern recognition applications are identified below. Developments in these areas are providing commercial-off-the-shelf (COTS) visual ATR capabilities that are appropriate for the force sustainment and product assurance tasks.

- **Robotics.** Close-range pattern recognition technologies are being developed for assembly line inspection and component handling.

- **Medical Analysis.** Medical image analysis tools are being developed for MRI, CAT, mammography and microscopy applications similar to Air Force non-destructive analysis tasks.

- **Video and Multimedia Processing.** Digital video image processing and multimedia hardware and software are applicable to some screening and bulk filtering applications.

- **Query-By-Information-Content (QBIC) Database Management.** QBIC query and retrieval technology capable of handling image data as well as text can provide supporting technology for context-based reasoning ATR in security and material control applications.

Pattern Recognition Technologies for Geospatial Information

The rapid and expanding development of commercial GIS technology provides the Air Force an opportunity to leverage spatial data technologies to enhance the context-based ATR systems in support of broad area situational awareness tasks. These technologies include:

- **Spatial Data Structure.** Efficient, linked data structures are being developed to handle the wide variety of vector, raster, and non-spatial data sources needed. Commercial standards and the National Spatial Data Infrastructure (NSDI) initiatives should be leveraged.

- **Spatial Reasoning.** The ability to measure, apply spatial logic and infer spatial and contextual knowledge in the context of dynamically changing spatial data is being developed to assess the "meaning" of geospatial data.

6.2.5.4 Impact on Affordability

Once developed, mature pattern recognition technology will improve the affordability and cost-effectiveness of systems and processes (in the previously stated Air Force mission areas) in three ways:

- **Reduced System Cost.** The introduction of ATR into selected systems—as a replacement for manual recognition—will reduce multiple operator displays, mensuration tools, and the training programs necessary to train and support human analysts and operators. As the ATR systems meet or surpass human operator performance levels, confidence in the systems will increase, reducing the need for backup displays and tools to permit operators to review "raw" data. The operational costs for human analysts (e.g., image analysts) and operators will be reduced as the ATR systems accept an increasing level of the data analysis tasks. This savings can be expected to be analogous to the savings accrued by BIT for complex avionics systems. Quantitative measures of reduced cost in any specific weapon system may be measured as: (1) reduced cost of displays— controls and operations and maintenance (O&M), and (2) reduced human training to perform manual analysis.

- **Enhanced Operational Efficiency.** ATR will reduce the low-level workload on warfighters, eliminating the review and detailed analysis of "raw" data, freeing the warfighter to concentrate on higher-level tasks. Reliable ATR detection and identification, coupled with automated situation assessment capabilities, will permit humans and weapon systems to more effectively monitor, measure and target hostile targets. Fratricide, mission planning errors, and overall situation uncertainty will be reduced. Quantitative measures of enhanced efficiency in any specific weapon system may be measured as: (1) improved reaction time to

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decision, (2) increased decision accuracy, (3) reduced decision uncertainty, and (4) expanded coverage rate.

- **Improved Operational Reliability.** As the confidence (measured as a posterior probability of correct recognition) of ATR systems increases, the operational reliability of the surveillance and targeting processes will also increase. Quantitative measures of operational reliability in any specific weapon system must compare process reliability considerations (human versus machine decision reliability) rather than a simple hardware reliability.

6.2.5.5 Recommended Development Plan

We recommend that the Air Force: (1) initiate a focused effort to develop a fundamental theory to aid in development and evaluation ATR systems; (2) expand the model-based technology developments for imagery to include full hybrid ATR including all-source context; (3) expand and coordinate technology developments to extend model-based reasoning to multiple-sensor applications; and (4) leverage commercial neural network, image understanding and spatial database technologies to augment model-based ATR with additional contextual data.

We recommend:

- **Expand the model-based technology development for imagery to include hybrid ATR including all-source context**

The Air Force should expand its development of model-based ATR capabilities for imagery, focusing on the detection and identification of critical targets.

Specific recommendations and milestones:

- Expand research to refine understanding of key phenomena to enable accurate all-aspect, all-condition target modeling. Expand worldwide clutter modeling to allow background models to be incorporated in the feature prediction process.

- Develop, by the year 2000, efficient and compact methods to represent and store complex target models (up to 200 types in 60 aspects and 25 configurations).

- Explore and quantify the benefits of complementing target models with surrounding context models (e.g., scenario and behavioral models) that will permit other data sources to be incorporated into target decisions.

- **Expand and coordinate technology developments to extend model-based reasoning to multiple sensor applications**

Increase model-based R&D to include model-based multiple sensor/phenomenology fusion to ensure that single-sensor ATR solutions can be extended to multiple sensor applications. In some cases, a multiple-sensor solution may be the only approach that achieves the stringent performance demands stated earlier in this Volume. Research in multiple sensor model-based reasoning processes should be initiated as the logical extension of current R&D activities focused on SAR data.

Specific recommendations:

- Identify the key sensor combinations in each representative task area and the necessary features and measurement accuracies that permit reliable discrimination.

- Define and develop the multiple sensor phenomenology base necessary to support multispectral modeling. This activity must be coordinated across services.

- Develop multispectral indexing methods (both sequential search and concurrent indexing of multiple models in different spectra) to efficiently reduce the model search space, search time and feature prediction. Demonstrate this by the year 2000.

- **Leverage commercial neural network image understanding and spatial database technologies to augment model-based ATR with additional contextual data.**

Beyond model-based matching, ATR research must evaluate the methods of applying reasoning processes (employing uncertainty management) to apply complex contextual data to the recognition process, such as:

- Precision spatial (geospatial, aerospatial) data

- Temporal behavior of entities and events

- Relationships to other entities and events (spatial, spectral and temporal relationships)

The large commercial investment in neural networks, image processing and GIS provides an excellent base of technology with potential selective application to the higher-level reasoning necessary to apply contextual data. The Air Force should conduct a technology audit of these commercial capabilities and conduct selective laboratory-level technology demonstrations of these capabilities applied to context data integration and reasoning.

Specific recommendations:

- Conduct a technology audit of key, pacing and emerging-embryonic commercial technologies and relate the potential of each to the generic ATR problem and the specific mission-area applications cited in this Volume.

- Identify the most promising commercial technologies and develop strategic R&D coordination activities over the period 1996 through 2003 with receptive commercial developers. (This may include focused small business innovation research [SBIR], or STTR solicitations, or cooperative research and development agreement [CRDA] arrangements as appropriate.)

- Select and acquire the most promising and available technologies that may be integrated with on-going Air Force ATR lab demo systems.

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- Plan, integrate, and conduct an evolving demonstration of ATR focused on a specific mission application that incorporates precision, real-time contextual information.

6.2.6 Unattended Ground Sensors (UGS)

6.2.6.1 UGS Overview

The Air Force is in a unique position to capitalize on the combination of unattended ground sensors with its reconnaissance and surveillance aircraft for an improved picture of the battle area. Airborne collection or relay is necessary to overcome the extremely short radio horizon of the ground sensor.

Unattended ground sensors fall into two categories and could serve a variety of purposes. Tags are used to mark targets of interest to allow tracking, and larger sensors are used to provide surveillance in an area of interest.

Mobile Targets

Smart sensor fields will provide timely and accurate data on the status, movement, and location of critical targets. UGS satisfy the needs of continuous surveillance of selected geographic areas, detection and reporting in real time, and reduced risk to personnel. They will provide identification of vehicular types and critical payloads, and provide activity indicators at ground sites of interest. They will also provide bomb damage assessments (BDA) of remote targets. Some studies indicate that modest numbers of UGS sites have potential to reduce TBM launch rates by 70-80%.

As depicted in Figure 6-22, UGS missions would provide detection, classification and tracking of critical targets (TBM, C2, etc.) and their reload sites. A long range array would be seeded over potential hide, reload and fire sites. Missions would support monitoring, reporting and interrogation of the sensors. Low power data fusion could allow sensor packages to communicate between each other to derive vehicle height, weight, number of axles, wheel base, engine type, number of cylinders, transmission type, and spurious emissions. Threat buildup would be derived from information reported by the site sensors. Types and quantities of vehicles entering and exiting the target area would be apparent. Choke points could be monitored to provide unit specific activity. Associate multiple vehicles would provide recognition of unit movements. Particular units could be identified by their unique features. This would provide cues to their identity so that each unit's activities could be tracked. There would be confirmation of hostile activities such as the identification of specific vehicles and events, and the reporting of movements before and after launch events. Sensors would be highly valuable in bomb damage assessment. They would provide intelligence about time and location, and would monitor sites for secondaries and on-site post attack activities.

6.2.6.2 UGS Deployment Concepts

The primary concern with the use of UGS is the ability to insert the devices into areas of interest. The following concepts are suggested:

- Overrun area—leave sensors in place

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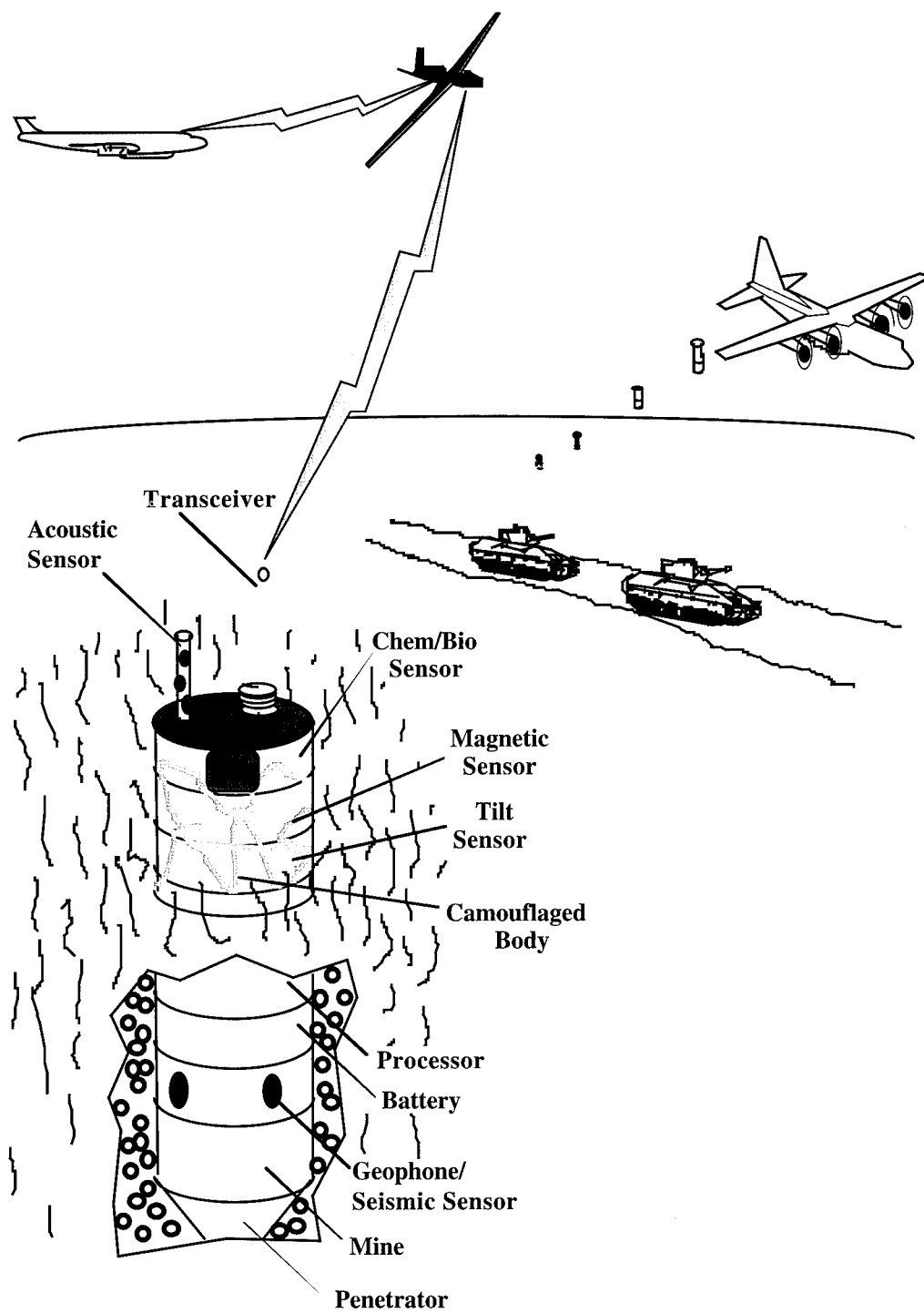
Figure 6-22. UGS Employment Concept

- Fly over—canister dispensed

- Fired from gunship 105 mm

- Injected with ground fired 105 mm

- Balloon borne canisters at night

- Glider launched from high level offset aircraft

- SOF hand emplacement

- Agent hand emplacement

- Trained animals

- Mobile micro machines

Access Through Nanomachine Technology

Even restricted areas need air, which suggests that an approach of close-in access would be through the exhaust air vent. The blower is usually in the intake line and the exhaust is easier to detect from its thermal signature. The ideal explorer would be a micro machine bee, but a practical version is off in the future. A suggested machine would be able to fly and crawl into optimum positions for successful monitoring. Today, small tracked vehicles are readily available in the commercial world, and in the future could be equipped with the intelligence and mechanics needed to navigate a duct that has been designed to make passage difficult.

The military use of these remote controlled vehicles would provide useful transport of close-in sensors, like magnetometers. If these crawlers were equipped with cutting tools (Figure 6-23), and they had access into ventilation systems, they could move freely throughout bunker complexes, detecting speech and various emissions of interest. A turtle-like rock with treads on the bottom as shown in Figure 6-24 could be moved in quite close. The machine could also be removed after the insertion or sample is completed. A simple approach would be to separate the collection package (rock) at the target and recover the tractor.
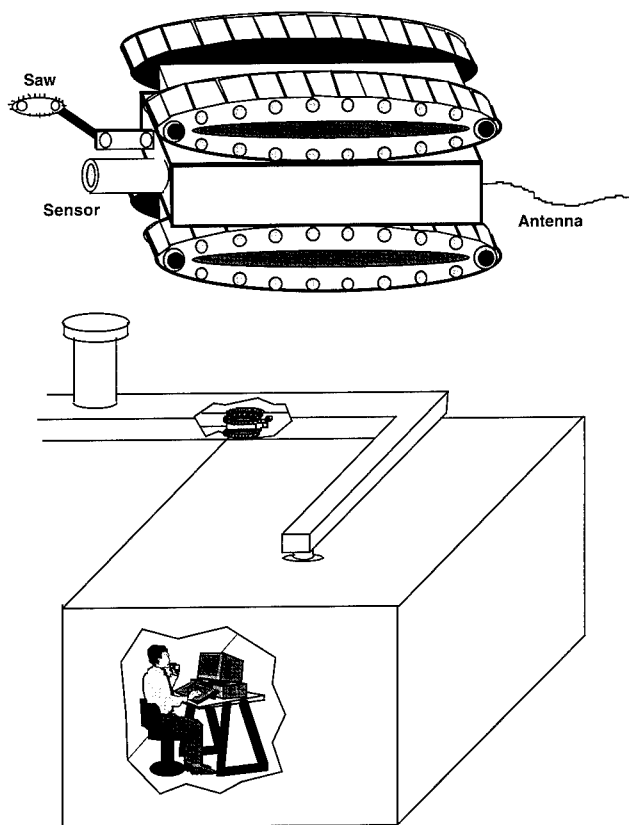
Figure 6-23. Two Track Machine
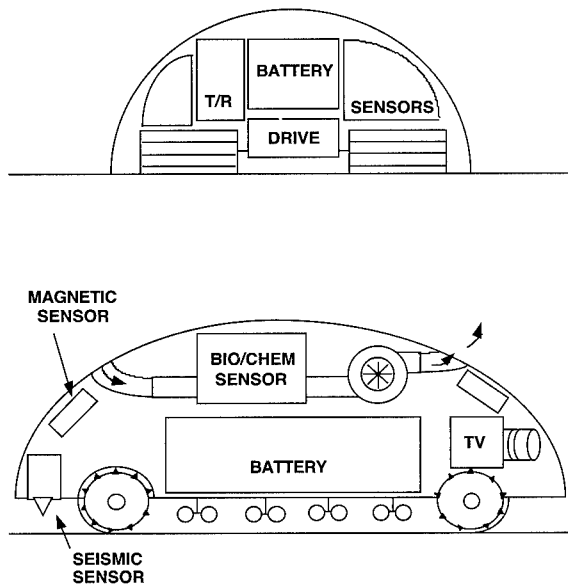
Figure 6-24. Mobile "Rock" Sensor

6.2.6.3 UGS Technologies

Magnetic Sensors

Passive detection, localization, and tracking of targets are possible using magnetometers. Classification of targets could be done with information from magnetic dipole strength, height, size and distribution. Coherent array processing can significantly extend the effective range of the magnetic sensor by increasing sensor directivity and array gain.

Higher frequency magnetics will provide sensing of vehicle alternators, electric fuel pumps, automatic controls for fuel mixture and, when available, ignition coil magnetic fields. If radio equipment is turned on, magnetic emanations from chopper power supplies can be detected also. Power generators are an excellent magnetic source in the 50 to 60 Hz spectrum. Load changes will reveal the activity of the installation.

A line array of magnetometers distributed along electric power lines will allow current monitoring to detect where significant loads are located. This may well reveal the location off large high value buried facilities. Once they are located, magnetics can also sense the distinctive magnetic fields from elevator motors, determining the number of elevators and the number of floors being used.

Acoustic Sensors

Using acoustic sensors would allow evaluation of both time-domain and frequency-domain algorithms for reducing processing and communications by performing peak detection processing and bearing and sound levels processing. Human speech carries very well along with all the other expected battle area sounds.

Nuclear Radiation Detection Sensors

Arrays of fielded sensors that have the capability of detecting nuclear weapons as they pass would be of extreme importance to give warning of their presence in the field.

Tilt Monitoring Sensors

The use of a tilt monitor sensor will allow the relative weight of vehicles passing on the road to be determined, providing further information for classifying unique military vehicles and their loads.

Infrared Sensors

IR sensors can detect heat radiated from vehicles, machinery and people, allowing the detection and classification of activity around the target area. Multispectral IR sensors can also classify or identify effluents. They would also allow determination of the status of industrial and other facilities. The air exhaust temperature from bunkers could be measured, providing data useful in making bomb damage assessments.

Subaudio Seismic Exploration

The elephant has been found to communicate great distances using his trunk as a very low frequency resonator. Long horns on some prehistoric animals were actually subaudio resonators used to communicate significant distances. These subaudio frequencies propagate much better than our normal audio range. The sounds of weapon detonation have been used to locate artillery and mortar fire in both world wars and Korea. The use of low frequency energy detection will take advantage of the enhanced propagation and reduced background noise to locate targets.

Sensor Detection of People at Rest or Asleep

A subaudio sensor will allow the detection of human respiration, a rate that is typically 0.28 Hz. The fixed ground sensor can carry out a FFT to process the data. A two minute sample will provide a 0.03 Hz effective bandwidth to sort out background noise from the respiration of people. The body oxygen requirement will keep the average respiration rate constant even when speaking. Multiple people would spread the response peak and also give a readiness state by seeing the increased rate respiration for active excited people. The use of diode impulse radar sensors could also detect human respiration.

Underground Bunker Detection Using UGS

To locate or confirm the presence of deep bunkers, factories and tunnels, sensors could be used to sample power line current along lines and cables, detecting current drops at the bunker area. Additional sensors with seismic capability could be spread in the suspect area allowing detection of machinery noises such as elevator motors, blowers, and so forth. Subsurface sounding similar to those used for oil detection can be carried out by using a seismic impulse from a shell or bomb in time of combat or sonic booms and thunder for covert probing. The multiple sensor seismic outputs processed in parallel can be used to develop the subsurface geological structure or tomographic picture with the unusual artifact of the target structure.

The same sensors could be used to determine bomb detonation locations and provide error correction for follow-up strikes. Power line current transits and load drops would provide a measure of bomb damage assessment.

Chemical Sensors

Volatile organic chemical (VOC) sensors are composed of two layers: an attractive material that detects the presence of the substance of interest, and a conductive material to carry electrical current to the electronics. They can detect airborne hydrocarbon fumes to 5 ppm with potential down to 1 ppm. The sensor reverts back to its original electrical state after the VOC has dissipated.

Multigas sensors based on organometallic microsensor arrays using a gradient doping process can be used to fabricate an array of microsensors with different composition and electrical response to enable the array to sense a number of gases. This would allow the detection of hydrocarbons, explosives, and nerve agents, and would be reusable by heating the array.

Close-in Jammer/Sensor

Search radars and SAM radars are high on the list for sensor coverage. The sensors would be able to detect readiness, and if the sensor had a low power noise jammer capability, the sensor could mask incoming aircraft over broad sectors. The mask could be remotely applied in irregular patterns to lead the operators to consider it to be an equipment bug since no airborne source is present.

Weather Sensor Module

Accurate and timely weather data from the target area could be very helpful. The most useful sensors related to weather would be solar flux, precipitation, and dew point. Ground visibility could be derived by measuring the received intensity of a pulsed laser diode's IR radiation at neighboring sensors. A broad field of sensors would give a timely and accurate local weather picture. Environmental sensors would provide data for accurate characterization of acoustic signal propagation for increased accuracy.

New Surveillance System Concept

Another concept is to exploit the LEO communication satellites that are expected to become ubiquitous, coupled with an array of UGSs to track aircraft in flight. This concept would work by detecting the near forward scatter of the communication beam by the aircraft with a receiver on the UGS. Similar concepts using earth based transmitters, such as television stations, have been examined in several different contexts over the past few years.

There are two principal applications. One is for technical intelligence, say, with covert receivers near a flight test center. The other is for air defense against a mix of conventional and stealth aircraft. For technical intelligence, the concept has some promise. If the UGS system has sufficient processing to decide when to report data through a covert link, one could monitor the activity in a small area, say a flight test facility, without advanced warning of an interesting test.

To be useful in an air defense mission, a potential surveillance system must couple to a weapon. To do that with this concept, the system must track an aircraft long enough and accurately enough to vector an interceptor close enough for its onboard sensor to acquire the target; the smaller the signature of the target, the closer the spacing must be. To accomplish this, the receivers must cover a large area and be dense enough and well enough integrated to have accurate tracks despite ghosting, false targets, track association problems and the like. For near and midterm situations, these bistatic techniques are more cumbersome and expensive than conventional radars. This will change only if the signature of the threat is reduced significantly below current estimates, and the difficulty and cost of the internetting must be significantly reduced. The Air Force should consider this concept if it faces a threat that is significantly stealthier than anticipated today.

Information Warfare Support Sensors

As this new area of combat emerges, unattended ground-based sensors will be an important part of accessing and disrupting the opposition's equipment. A wide field of attack from close-in monitoring of activities and usurping control or insertion of disruptive data to their system will need proximity. The generation of EMP to destroy equipment in the local area could also be a potential use of sensors. Significant efforts will be required to insert these devices and then collect and control their operation, but it should certainly be a strong area of involvement in the future. Careful coordination of these efforts will be required for their optimum use.

Countermeasure Ground Sensors

When the enemy's sensors can be located or the locations predicted, a line of friendly devices with countermeasure features could be deployed to produce moving acoustic, seismic, magnetic signatures for our tanks that could be used to lure hostile fire and reveal the enemy's location.

Data Link Considerations

Reducing the data link power would be an important technology area that would reduce sensor size. The use of large aperture antennas on platforms like AWACS and JSTARS would provide a power reduction in the order of 1000 by having increased gains of 30 dB over normal data link antennas. This will reduce the battery the same ratio, a major size and weight benefit. This is of particular importance for tagging applications that must be placed on a target and not be noticeable to the user.

Simple Cross Links Between Fields of Sensors

Since most ground sensors are seismic, it seems reasonable to use this capability to provide covert communication links between fields of sensors. Data could be sent on a subcarrier outside the normal band of interest. Considerable power savings may be possible over the expensive spread and hop technology.

Recommendations

A strong push to develop low-power sensors with multiphenomenon sensing elements should be carried out. Their construction should allow stacking of the individual sensing elements into a logic control module to meet specific battlefield concerns. Table 6-6 lists a number of sensing elements and their applications. There should be the development of fusion techniques to display all source data with sensors. Early fielding of feasiblility models will provide needed insight into their capability and proper mix to derive target identification. All source intelligence fusion must be pursued with ground sensors to provide a new level of battlefield awareness.

6.2.7 Miniature Detectors for Chemical and Biological Agents

There are a number of missions that require detections of chemical and biological agents. These include treaty monitoring, counter proliferation and battlefield warning to aid in the use of protective measures. For many of these missions, small sensors can be widely deployed, either on UGS or miniature UAVs. There are a number of technologies that make that possible. These technologies are reviewed in this section.

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Table 6-6. Sensing Applications

Sensing Techniques	Vehicles/Tanks	Troops	Overhead A/C	Stealth A/C	Tel	Bunker	SAM	Large guns	Wx
Magnetics	X				X	X	X	X	
Seismics	X	X	X	X	X	X	X	X	
Tomograph						X			
Acoustic	X	X	X	X	X	X	X	X	
IR	X	X	X		X	X	X		
NBC					X	X			
Tilt	X				X		X		
Solar flux dewpoint									X
Close-in comm/ radar jammer	X	X					X		
EMP gen.	X	X			X		X		
Cable access						X	X		
SIGINT freq. trigger	X	X			X	X	X		
Impulse radar element	X	X			X				
LEO-Bistatic radar			X	X					
I&W emulator	X	X	X	X	X				

6.2.7.1 Near Surface Meteorologic Measurements with Radio-Acoustic Sounding Systems (RASS) Technology

Background

Attacks on WMD facilities could result in the venting of lethal materials into the atmosphere producing significant and undesirable collateral effects. The dispersion of these materials will depend on the local atmospheric conditions (particularly wind vectors) and surface topography. A system has been demonstrated using RASS technology that measures the local vertical profile of winds and temperature. These measurements were obtained from small piezoelectric transducers that emit pulses of acoustic energy vertically, and a microwave radar is used to scan the subsequent motion of the acoustic pulses. Lateral motions of the acoustic pattern determine the horizontal winds as a function of height, Doppler shifts indicate vertical winds, and sound speed variations infer temperature. This meteorologic information, possibly obtained from an array of sensors, can be combined with GPS location and stored terrain information as input to a computer model for the prediction of local weather patterns and the subsequent dispersal of venting aerosol agents.

Approach

The RASS is capable of measuring vertical wind and temperature profiles directly above the deployed system to heights of a few hundred meters. The RASS can be battery operated and deployable by one man, or air dropped into an operational area. A system of this type could be constructed with a mass less than 30 kg, a power consumption of less than 100 watts, and a volume less than 0.4 m³. The system can be designed for unattended remote operation and with advanced modeling would be capable of delivering aerosol dispersion predictions in minutes.

By scaling current RASS technology to higher acoustic frequencies, a small, highly directional acoustic source can be developed. Operation at acoustic frequencies of about 10 kHz limits the effective range of the system to several hundred meters altitude due to attenuation of the acoustic signal. This, however, is sufficient to provide the information necessary for local wind-prediction modeling. At these acoustic frequencies, the transducers are physically small piezoelectric elements. These transducers can be baffled in such a way as to provide a highly directional acoustic pulse. The size of the baffling needed to suppress side radiating acoustic energy is greatly reduced by the choice of an operating frequency of 10 kHz.

The radar wavelength is chosen to be twice the acoustic wavelength so that a resonant backscattering condition is formed. By selecting a shorter acoustic wavelength, approximately 3 cm in this case, a short RF wavelength is specified. This short RF wavelength allows the use of physically small, highly directional, phased-array antennae for the microwave radar. A man-portable, field-deployable Doppler radar of this type has been built, and previous systems have used small, 0.25 m by 0.5 m, planar antennae. This same technique can be used for a counter-proliferation system. The receive antenna would be a moderately wide-beam angle, zenith staring, planar antenna. The tracking of the acoustic pulse would be accomplished by electrically steering the transmit antenna, a narrow-beam, planar, phased array.

In operation, an acoustic pulse would be emitted every few seconds. The radar would then interrogate the pulse every few microseconds. The radar reflects resonantly from the sound pulse as the pulse is carried by the wind field. At these pulse rates, a wind field of approximately 1 m/s to 10s of meters per second can be measured. By chirping the radar frequency, the center frequency of the resonance condition can be measured and used to infer the vertical temperature profile.

This system would carry a small GPS receiver for self-location. The GPS information would be used to retrieve previously stored terrain information for use in the predictive model. The GPS time information also can be used for time correlating measurements from an array of deployed stations. These local, near-surface measurements could then be combined with a single distant (100-km height) wind field measurement up to the boundary layer or coupled to large-scale, gridded forecasts as input to a modified version of existing meteorological and dispersion codes such as HOTMAC and RAPTAD. The single distant measurement can be accomplished using ground, airborne, or space-based assets. The new local, near-surface measurements will allow great improvement in the prediction of local plume dispersal. A key part of the modeling aspect is to determine the best way to integrate the local measurements into the models.

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6.2.7.2 DNA-Based Point Sensor for Identification of Specific Microorganisms

Background

Biological species identification using DNA techniques has been demonstrated widely. It is possible to optimize, engineer, and militarize DNA-diagnostic technology, providing a fully automated "point detector" for the rapid identification of microorganisms. The fundamental processes to be optimized for this sensor are the polymerase chain reaction (PCR) that amplifies biological-agent DNA strands, and capillary electrophoresis (CE) that allows identification of the DNA produced. The near-term, first-generation of this sensor system has a projected weight of 70 lbs, and target biological-agent identification time of about 15 minutes, and will be designed and packaged for fielding on a mobile platform such as the Army Biological Integrated Detection System (BIDS). In the more advanced second-generation system, the PCR and CE functions will be carried out on a "chip" that plugs into a hand-held "reader." The projected weight of this hand-held system is less than 10 lbs, with an agent-identification time of 2 minutes.

Identification of characteristic DNA strands is a dependable way to conclusively identify biological organisms. This technique is so powerful that even a single strand of DNA can be amplified to measurable levels using PCR. After PCR amplification, analysis of the products is required to allow identification of the specific biological species from the characteristic DNA signatures. This analysis is commonly done using slab-gel electrophoresis. Presently, both the standard PCR and slab-gel electrophoresis processes are complex, involve a variety of delicate labware, require continuous man-in-the loop operations, and are highly time intensive with a typical biological-agent analysis requiring several hours. The automation, engineering, and packaging effort proposed here will eliminate all these present operational complexities and provide a fieldable system for the rapid identification of microorganisms.

Approach: Mobile-Platform, DNA-Based Point Sensor (Flow-PCR)

Using demonstrated hardware components and a continuous fluid-flow approach, the mobile-platform "Flow-PCR" device will consist of a rapid thermocycler to execute the PCR process and an integral CE system with fluorescence detection to analyze the PCR products. With the exception of periodic servicing, all facets of this device will be completely automated, including the data analysis and reporting.

Fluid Handling: Segmented flow analysis (SFA) techniques, using standard metering pumps and injection valves, will automate sample and reagent handling. PCR reagents (Taq polymerase, buffer, primers, and fluorescent dye) are injected after the analyte solution is concentrated by ultrafiltration. The SFA process injects an air bubble before and after the sample/ reagent mixture to create bolus or plug flow, which keeps the reagents well mixed and accelerates the PCR amplification process. Two marker DNA segments will be added to the sample/reagent bolus. These "internal standards" will confirm PCR amplification and verify the CE analysis.

Thermocycler: In commercially available PCR instrumentation, most of the amplification time goes to warming and cooling the aluminum block that holds the sample vials. In the Flow-PCR system, the sample/reagent bolus will flow through a Teflon capillary wrapped around a

mandrel. The capillary will carry the sample/reagent bolus repeatedly through three heat-exchange chambers. Each chamber will be held at the optimal temperature for one step in the PCR amplification process. Thirty-second PCR cycles have already been demonstrated using air heating and cooling in a sample vial. At this rate, 30 PCR cycles are completed in 15 minutes. This is 20 times faster than current instrumentation and demonstrates the potential for Flow-PCR.

Capillary Electrophoresis: Coupled with laser-induced fluorescence (LIF), CE will be used for analysis of the PCR products. Ten-minute analysis times and high resolution have already been reported for CE sizing of DNA strands from 100 to 1500 bp. After each sample analysis, the column is refilled with linear polyacrylamide gel. Reproducibility of better than 1 percent relative standard deviation (RSD) is routinely reported from run-to-run using this technique, and the presence of DNA markers improves reproducibility to better than 0.2 percent RSD. Using multivariate statistical data analysis methods, the same performance can be achieved in less than half the time.

Fluorescence Detection: Fluorescence has been demonstrated for very sensitive DNA detection with CE sizing. Sub-nano-gram quantities have been detected. The exceptional sensitivity of LIF means less amplification time, and fewer PCR cycles are required before CE analysis.

Approach: Hand-Held, DNA-Based Point Sensor (PCR-Lite)

PCR-Lite will combine the understanding developed in fabricating and fielding the Flow-PCR with emerging technologic advances in CE on a chip. Analysis times of 2 minutes for the miniaturized PCR-Lite are anticipated. CE on a chip has been demonstrated as a fast, accurate means for doing electrophoretic separations, with analysis times reported in milliseconds rather than minutes.

Using microlithographic fabrication techniques, PCR and CE can be put on a substrate the size of a microscope slide. The disposable slides will be pre-loaded with reagents and replaced after each analysis. Small sample volumes will allow very rapid and efficient peltier heating and cooling of the PCR chamber. The slide will fit into a hand-held "reader" that contains the power supply, the laser (or LED), the detector, and the peltier device. The entire system will weigh 5 to 10 lbs.

6.2.7.3 Biological Toxin Identification with Matrix-Assisted Laser Desorption/ Ionization Time-of-Flight Mass Spectrometry Point Sensor

Background

It is possible to develop and demonstrate a field-deployable point sensor, based on Matrix-Assisted Laser Desorption/Ionization Time-of-Flight Mass Spectrometry (MALDI-TOFMS), to detect and unambiguously identify biological toxins. The sensor system is intended for deployment on stationary platforms for fixed asset monitoring (docks, bases, staging areas, etc.) or mobile platforms for reconnaissance, early warning, and bomb damage assessment. The sensor system will operate autonomously and continuously with only periodic (daily) servicing, be capable of toxin analysis and identification times of less than 10 minutes, and be easily programmable for new toxins. The near-term, first-generation system will not be man-portable,

but rather designed for integration into an Army BIDS-like platform, and possibly a UAV. This system will weigh about 100 lbs, occupy a volume of approximately 3 cubic feet, and require on the order of 500-W power. The sensor system will be capable of integration into Command/Control systems, or function in a stand-alone mode.

Toxins are poisons resulting from the natural metabolic process of certain microorganisms, plants, and animals. These chemical compounds may be relatively small (e.g., alkaloids), but are often complex, high-molecular-weight species such as proteins. The neurotoxin botulinum type A, with a molecular weight of 150 kDa, has a greater casualty-producing potential than VX, the most lethal nerve agent. With the availability of a large number of readily producible biological toxins, and the ease of development of these agents in tactical, strategic, and terrorist operations, it is critical that sensors capable of detecting and identifying these agents be developed. Fortunately, the unique mass-spectral signatures of the toxins can be used to characterize the threat.

Technology for the rapid identification of large biomolecules, characteristic of biological toxins, has recently taken a significant step forward with the development of MALDI-TOFMS. With this technique, the biomolecule analysis is initiated by mixing the sample (which can be an aerosol, liquid, or solid) with an excess of an appropriate matrix material. A small aliquot of the sample/matrix solution is then applied to a probe that is introduced into the mass spectrometer. Pulsed ultraviolet laser light is absorbed by the matrix, leading to the desorption/ablation of part of the surface. Protonation, cationization, or electron capture reactions then occur, resulting in the production of *intact* high-molecular-weight ions of the analytes. Time-of-flight mass spectrometry is the method of choice for ion detection, due to the pulsed nature of the ion source and the sensitivity and high mass capabilities of TOFMS.

The advantages of MALDI-TOFMS include: (1) the ability to directly measure the mass of biological toxins up to 500 kDa; (2) speed of analysis (< 10 minutes); (3) high sensitivity (only picogram amounts of the target compound are needed); (4) simple, rugged instrumentation; and (5) the potential to identify microorganisms before they begin releasing a toxin. This last point is important because some BW agents do not become pathogenic until they are incorporated into a host (soldier or civilian).

The mass characteristics of bacterial toxins lend themselves well to detection by MALDI-TOFMS. In addition, some toxins require the presence of other compounds in order to express lethality. Many of these "promoters" are also high mass species that can be detected using this sensor technology. Correlation of toxin and promoter presence will provide additional confidence in the analysis.

Approach

The development of a field-deployable, biological-toxin detection and identification system can be based on MALDI-TOFMS technology. Although simple, once-daily servicing of the system during periods of continuous operation are required, a fielded system could be completely automated, including data analysis and reporting. Development of a prototype system will involve efforts in the following areas.

- Optimization of matrix chemistry and composition including use of multiple or mixed matrices and definition of optimum measurement conditions.

- Development of a toxin signature library.

- Vacuum System: Pumping systems require the latest vacuum-system technology to be as small as possible, while still retaining the ability to evacuate the system to high vacuum in a reasonable time (< 5 min). The sample probe needs to be miniaturized, and automatic sample preparation and loading devices are needed though this may be the only physically moving part of the sensor system.

- Laser: Because only very low pulse energies (often < 1 microjoule/pulse) are required for MALDI, compact laser sources can be utilized. Small (cigarette-pack size) ultraviolet lasers are now commercially available and can be integrated into the fielded system.

- Mass Spectrometer: Recent experiments in the literature indicate that acceptable mass resolution can be achieved with flight tubes less than a foot long.

- Electronics and Data Analysis: High-speed digitization is necessary to faithfully record the mass spectral data. The identification algorithms, capable of picking out the desired toxin signatures in potentially complex mixtures, need to be developed and tested. Minimization of false reports (positives and negatives) is of particular concern.

6.2.7.4 Smart Film Microsensor for Detection and Identification of Chemical-Warfare Agents

Background

Sensor technology is needed in the counter-proliferation program for the rapid *point* identification and quantification of the entire suite of chemical-warfare agents as well as the detection of signature chemicals (precursors, degradation products, and solvents) associated with their manufacture and distribution. The specific needs include (a) hand-held or ground-based sensor systems for passive defense (troops, bases, supply depots, etc.), (b) ground-based sensor systems for target characterization, and (c) UAV deployed sensor systems for bomb damage assessment, and (d) a hand-held point sensor for covert activities.

An autonomous portable sensor is feasible for sensitive, rapid, real-time detection and quantification of the entire class of chemical-warfare agents (except HCN) and selected signature chemicals. The notional sensor will be a low-cost, compact, lightweight, rugged instrument weighing a few pounds and consuming less than 10 W of power.

The microsensor is based on technology originally developed for rapid tracking of organic toxins in air. Novel surface modification techniques (molecular "self-assembly") have been used to *covalently attach* reagents that are *specific for the molecule of interest* directly to an acoustic device surface, resulting in microsensors of great stability and sensitivity. The guest-host interactions between the reagent attached to the transducer surface and the organic toxin are reversible, thereby allowing real-time detection of the molecule of interest. A laboratory sensor prototype has been built based on the marriage of a cone-shaped molecular "bucket"—

called cyclodextrin—and commercially available SAW technology. Through selection of different cyclodextrins (a-, b-, and g-) that have different "bucket" sizes and the chemical modification of these reagents, it has been possible to tune the specificity to different target toxins. Each of these different reagents has a distinct "fingerprint" type response to different toxins and through the use of an array of these smart film SAW sensors, it is possible to identify and quantify multiple toxins in a complex mixture.

Current SAW sensor technology relies on polymer films that are limited in several important ways. First, these films are typically spun onto the SAW transducer surface and the absence of direct bonding leads to failure by delamination. Second, these polymer films are not tailored to specific target toxins and typically respond to a wide variety of different potential interferents resulting in false positive signals and extremely poor capabilities for identification of specific toxins. Third, polymer films are not adapted to specific CW toxins and, therefore, are not very sensitive; efforts to make them sensitive by increasing the polymer thickness leads to poor response times, material stability, and reversibility.

Approach

The general approach utilized here is adaptable to a wide variety of transduction methods. Acoustic transduction (specifically a SAW, transducer) is favored because of its simplicity, commercial availability and small size.

A cyclodextrin-based sensor has the potential to provide ultra-high sensitivity (~50 ppb level) for typical organics such as xylenes. Several different sensors have been fabricated using chemically modified cyclodextrin molecules and the response of each to a suite of organic and halogenated organic molecules was measured. Each sensor (with distinct cyclodextrin molecules) has a unique "fingerprint" response to the suite of organic toxins. It is possible, therefore, to identify and quantitate multiple species in a complex mixture by using an array of such SAW transducers. Existing technology can be used "as is" to develop sensor systems for many "signature" molecules.

This sensor technology can be applied directly for sensing CW agents with further modification of selectivity of the reagent layer; in effect, the selectivity of the sensor will be optimized for CW agents. Chemical selectivity can be enhanced by using a new host-sensing layer. Molecular specificity, sensitivity, and reversibility will be enhanced by attachment of functional groups (R) on the upper rim of calixarenes resulting in a deeper host bucket and wider upper rim, including the ability to tune the polarity of the calixarene "bucket" by adjusting the donor (D)/acceptor (A) characters. Calixarenes are a larger family of synthetic cyclic arene compounds (than the natural occurring cyclodextrins) whose characteristic sleeve-like-cavity shape is defined by the number of phenyl units. The inside of the cavity of calixarene exhibits hydrophobic behavior and depending on the cavity volume and polarity is just such a size and chemical environment to readily incorporate specific chemical agents and/or their degradation products via host-guest interactions. These calix(n) arenes whose size is tunable by varying the number of arene units *(n) only* form inclusion complexes with organic solvents via non-covalent bonding (van der Waals interactions) in much the same way as enzymes and substrates interact; as such, sensor specificity is achieved by the inherent molecular recognition properties of calixarenes thereby allowing for *reversible* binding of the analyte and continuous operation and near real-time sensing.

6.2.7.5 Enzyme-Based Electrochemical Sensor for Detection and Identification of Chemical Warfare Agents

Background

It is possible to development of a small, lightweight (< 1 lb), self-contained and battery-powered (AA size) electrochemical sensor system for the point detection and identification of the entire range of chemical-warfare agents. The sensor can provide both a warning of the presence of CW agents and a determination of the agent concentration, with response time in the minute range and sensitivity roughly in the ppb range. The sensor package would essentially be single use and thus disposable. The sensor-package configuration will depend on the deployment scenario, with typical shapes being 3 inch by 3 inch by 0.5 inch badge like, or 6 inch-long, 1 inch-diameter cigar-like. Specific counter-proliferation applications include (1) a hand-held sensor for covert operations, (2) an early-warning system for passive defense (docks, staging areas, bases, etc.), (3) a ground-based system for target characterization, and (4) a UAV-deployed system for bomb damage assessment.

The CW-agent sensor system is based on recent work using enzyme-based electrochemical sensors to monitor glucose. Enzymes are highly specific catalysts for chemical reactions, and the rate of formation of products from these reactions can be monitored electrochemically. A simple, highly-sensitive electrochemical sensor has recently been patented, comprised of a thin enzyme-loaded composite layer adjacent to a layer of electrolyte and sandwiched between two electrodes. The use of this thin-film composite structure is a significant improvement in electrochemical sensor technology because it dramatically increases the sensitivity per unit area and the robustness of the sensor. In operation, one of the electrodes (typically carbon cloth) allows diffusion of the CW agent into the enzyme-loaded layer. This gas-diffusion electrode provides a high-flux gas delivery mechanism, and the combination of the gas-diffusion electrode and the composite layer represents a unique approach to electrochemical sensors for a gaseous reagent. A sensor package including a polymeric electrolyte gel provides all needed reagents for the enzyme chemistry except for the substance to be analyzed (the CW agent), thus eliminating the need for any liquid phase reagents.

The application of this technology for CW detection relies on inhibition of enzyme action by the chemical agent, which results in significant decreases in the rate of generation of products from the catalyzed reactions. The sudden decrease in the electrochemical response of the sensor in the presence of the CW agent will provide an alarm indicating the presence of these chemicals, while the change in response level after exposure to CW agents will allow the determination of concentration. This electrochemical-detector configuration is ideally suited for deployment as a personal clip-on badge-like sensor for the detection and identification of chemical-agent vapors or aerosols. In addition, these sensors can be reconfigured simply for other deployment scenarios, such as a UAV platform.

Approach

To develop a complete electrochemical sensor package for the broad spectrum of CW agents, it will be necessary to tailor the active layers and carbon cloth to allow adequate transport of each class of reagents to the catalytically active site. The approach is to optimize the inhibition of certain enzymes by chemical-agent simulants in the highly sensitive composite layer.

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The enzyme inhibition chemistry has been widely reported. Examples of specific enzymes that are inhibited by CW agents include actylcholinesterase, cytochrome oxidase, and pyruvate dehydrogenase, each of which is suitable for a certain class of chemical agents. Enzymes that respond to the full range of chemical agents can be deployed. The effect of the agent is enzyme inhibition. Since the enzyme is a chemical amplifier, the deactivation of small amounts of enzyme leads to a large change in current. 10^{14} molecules of gas-borne agent (1 ppb in 20 l of air) will shut off enzyme equivalent to 160 mA of current.

6.2.7.6 Aerosol-Particle Capture and Fluorescence Detection with a UAV-Based Particle Collector

Background

For counter-proliferation (CP) applications, a UAV-based, aerosol-particle collection/detection system (ACS) could collect and analyze aerosol particles for bomb-damage assessment, target characterization, and battlefield passive defense. The ACS could provide analyses in real-time of the aerosol-particle concentration and size distribution, and detect biological aerosols by their UV excited fluorescence. The aerosol particles collected with this system could also be returned to base for post-mission analysis by battlefield or fixed-laboratory analytical techniques. The notional system is compact (~1 cubic foot in volume), light weight (< 15 lbs), and specifically designed for integration into a UAV.

A series of aerosol collectors have been developed to monitor airborne aerosol sizes and concentrations in cloud plumes that are released during AGEX tests. The collectors use cascade impactor techniques to separate out aerosols by size. The aerosol mass concentration ($\mu g/m^3$) in each of seven size fractions between 0.1 and 10 μm in diameter is determined. Aerosols of each size fraction are deposited onto a quartz-crystal microbalance that provides a real-time measurement of the aerosol mass. The present aerosol-collector system including pump, power supply, collector, and controlling electronics, weighs about five pounds.

The aerosol-collector is presently being incorporated into a small airborne measurement system called the micro-atmospheric measurement system (μ-AMS) that is designed for deployment on a UAV The μ-AMS system includes the aerosol-collector, temperature and humidity sensors, altimeter, airspeed sensor, fluxgate compass, and GPS receiver. The flight package weighs less than 15 pounds including the aeroshell that is 30-inches long and with a seven square-inch cross section. The system collects and measures aerosol concentrations during flight and transmits the data to a ground station in real-time. The remotely piloted vehicle (RPV) position and aerosol concentrations are graphically displayed to the ground-station operator so that the aircraft can be directed to areas of most interest within the aerosol cloud.

A series of handheld UV-excited fluorescence spectrometers have also been recently developed. These detectors were originally designed to monitor low levels of uranium by exciting contaminates that are present in very-small quantities within nuclear facilities. All of the instruments employ a UV-light source to illuminate a surface, and a spectrometer to collect the fluorescence spectrum. The most recent generation detector, including power supply, light source, fluorescent detector, and user data display, weighs only three pounds and is contained within a package volume of about 1/4 cubic foot.

Approach

As part of the development of the CP aerosol-particle collection/detection system, the fluorescent spectrometer and aerosol-collector technologies will be integrated. In addition to the real-time aerosol analyzer, a second collection channel will be added that collects a time-series of aerosol samples. This time-series sampler provides a set of discrete samples on which the fluorescence is measured as the sample is collected. Using this technique, the aerosol-particle is classified by size and fluorescence properties. Real-time analysis of the sample fluorescence spectra will be used to detect biological aerosols in a cloud.

The aerosol-particle airstream drawn into the ACS detector will be split between the real-time aerosol analyzer and the time-series sampler. Each will separate particles by size. The real-time analyzer will separate the particles in eight size ranges between 10 and 0.1 μm. The time-series analyzer will collect particles in two size ranges, 2.5 to 10 μm, and < 2.5 μm. Each collection stage of the time-series channel will be coupled to the fluorescence spectrometer using fiber-optic bundles that deliver the UV-light to each stage and collect the fluorescent light from the sample. Analysis of the fluorescence intensity and spectrum will be carried out within the detector package to determine, in real-time, if the collected aerosols are composed of biological material.

6.2.8 Expanded Sensing Dimensionality

Potential adversaries will continually seek means to reduce the effectiveness of our current weapon systems. From the perspective of mature imaging systems (including EO/IR and radar), which are dependent on the shape signature and reflectivity of the target relative to the background, this will result in the development of tactics and techniques to reduce the contrast (observability) of the target relative to its background. The key to holding the desired target at risk is to sense new and unanticipated target features. Thus the enemy could be using effective countermeasures that deny certain "conventional" image features while providing signature features in another image dimension. At this time, we have barely begun to make use of target dimensionality beyond the conventional three spatial dimensions. Wavelength/frequency, time, and polarization are other available but underexploited dimensions. Another form of multidimensionality is the use of sensors using alternate modalities, such as an acoustic sensor and an electromagnetic sensor or a SIGINT sensor and a radar. Sensor fusion is directly related to increased sensing dimensionality.

To increase the probability of target detection, recognition, or identification while maintaining a CFAR, we can use a limited number of target "dimensions" with very high resolution, or we can increase the number of orthogonal dimensions while making use of limited resolution in each dimension. Orthogonal dimensions in this context mean parameters which have non correlated false alarms. By expanding the dimensionality of target parameters, more difficult targets can be detected, recognized, and identified. Also, if data transmission or storage is an issue, limited resolution with expanded dimensionality will achieve higher performance with much less data bandwidth than high resolution using limited dimensionality.

Technology Description

There is great promise in increasing the dimensionality of the space in which target characteristics are assessed. A partial list of new sensing dimensionality with conjectured payoff/

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application is presented in Table 6-7. This list is not all inclusive but rather gives a broad indication of observability trends in both optical and radar imaging applications.

Several of the measurement techniques have been discussed previously in this Volume. Three additional concepts are described below. The first adds a new dimension to the sensing space (MS/HS/US). The second combines two sensors (acoustic and electromagnetic) in a fusion process. The third uses a portion of the RF spectrum that has not been used for high bandwidth imaging (wide bandwidth, low frequency, SAR for FOPEN or ground pen), and also makes use of polarization. Other expanded sensing systems are certainly possible. Vibration sensing can be expanded beyond what has been tested. Coherent laser radar has been used for vibration detection at 10 μm and recently at 2 μm. Polarimetry can be applied for expanded target detection/ classification, using passive IR, laser radar, or microwave. For example, polarization is used in the FOPEN/GPEN discussion in Section 6.2.8.3. Similarly, the time dimension can be more fully exploited in passive or active sensors.

Table 6-7. Expanded Sensing Dimensionality Opportunities

Target Feature	Sensing Method	Applications
Target Motion	Temporal response(Doppler) in active coherent systems Motion sensing by MEMS	Machinery activity provides vibration Aircraft engines provide modulation Target motion
Target and Clutter Geometry	Polarimetry in radar, passive IR, or laser radar	Enhanced target discrimination in clutter
Target and Clutter Material Gas Composition	Spectral response in reflection and/or emission, Laser Spectroscopy	Terrain Categorization Target material detection/ classification NBC detection
Penetrating Obscuring Media	Combined RF/acoustic earth penetration Use of wide bandwidth, low frequency SAR (uses polarization & an unexploited portion of a dimension)	FOPEN/GPEN detection of hiding targets Detect/characterize underground objects

6.2.8.1 Multispectral/Hyperspectral/Ultraspectral Sensor (Exploiting the Wavelength Dimension)

Description of Sensor Concept

Spectral sensors of this type produce images of ground scenes simultaneously in two or more bands in the thermal infrared (between a wavelength of 3 and 12 microns) with high signal to noise ratios, excellent band to band spatial registration, and very high band to band uniformity of response. That is to say, differences in the measured signal at one subband and another subband

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must be due almost entirely to differences in the sensed phenomena, not to a different response of the sensor from one subband to the other. Thermal infrared is chosen to obtain night target detection/recognition/ID capability; a 0.4 to 2.5 μm wavelength based sensing may also be used for daytime operation. Air Force and ARPA funded work (including tower based target and background spectral signature measurements) has shown that target signal to clutter ratios for detection of low contrast (CC&D) targets may be improved by over 20 dB with consequent reduction in false alarm rates for a given probability of detection.

Table 6-8 shows the distinction between MS, HS, and US.

Table 6-8. Multispectral/Hyperspectral/Ultraspectral Definitions

Class of Sensor	Definitions (either or both apply)	
	No. of Bands	Spectral Bandwidth
Multispectral (MS)	10s	0.1 micrometer
Hyperspectral (HS)	100s	0.01 micrometer
Ultraspectral (US)	1000s	0.001 micrometer

MS sensing is probably sufficient for target detection. HS or US may be required for target recognition or identification. As bandwidths become very narrow, an active illuminator may be required due to available signal to noise. This could lead to a tunable laser sensor for wavelength based target identification.

In the spatial domain, the trends include finer spatial resolution and greater area coverage. Beginning with 80-m resolution for LANDSAT MSS, LANDSAT TM reduced this to 30 m, SPOT to 20 m multispectral (and 10 m panchromatic), and future commercial systems are projected to have MS resolutions down to 15, 10, or 4 meters. Wide area coverage is an operational need, as is orthorectification, geo-referencing, and, potentially, generation of three-dimensional information.

Polarization effects in both reflected and emitted radiation have been known for some time, but their exploitation has not proceeded as rapidly as for ordinary spectral phenomena. Experimental sensors are now available. This is another expanded area of dimensionality.

Airborne and ground-based ultraspectral systems have been developed and tested for detection of gases, such as chemical vapors, CBW agents, and pollutants. Typically, these operate at LWIR wavelengths, where gases have distinctive absorption lines, and exploit differential absorption at adjacent wavelengths. Passive systems rely on having a temperature difference between the cloud of gas and its background and may have relatively coarse resolution. Active systems utilize laser radiation at two or more different wavelengths. An active system might continue to interrogate additional wavelengths until it achieves predetermined probabilities. Another type of US sensing could take advantage of Fraunhofer absorption lines in the solar irradiance spectrum (e.g., at visible wavelengths). Radiation in those narrow lines then is due to emission of hot sources (such as rocket exhausts) or to a wavelength conversion process, such as fluorescence, in which radiation at those wavelengths is stimulated by absorption of radiation at different wavelengths (this also occurs in ocean phytoplankton).

Relationship to Air Force Missions

The Air Force has a need to search wide areas with a high probability of detection, and a low probability of false alarm. Use of the spectral dimension allows us to use much larger pixels, and still discriminate against clutter. This in turn allows us to search large areas with acceptable false alarm rates. Without the use of this additional dimensionality, the required spatial resolution for acceptable probabilities would be prohibitive. In addition, the Air Force has a strong need to be able to detect partially obscured targets, either through foliage or camouflage nets. The use of the wavelength dimension can make this possible. Signal to clutter will be lower than for unobscured targets since the whole pixel is no longer filled with target, but so long as a reasonable portion of the pixel is filled with target it will still be possible to detect the target. Detection through foliage or camouflage would be very difficult with conventional means. Another area that has been identified is intelligence preparation of the battlefield. Multispectral remote sensing can provide useful inputs through generation of spectral categorizations of the terrain classes present in potential battle areas. Even the current 30-meter data from LANDSAT can yield useful products. HS/US systems have the potential to detect, identify, and map the dispersion of chemical agents dispensed in battlefield areas due to their selective absorption of infrared radiation. HS/US systems similarly have potential for detecting and identifying effluents from NBC production facilities which may be indicative of the existence and type of activity that is in progress. This capability might also be employed in a BDA role, to assess whether or not a target area was an NBC facility based on effluents released as a result of an attack and confirm a successful mission. One element of countermeasures against hardened/ underground facilities is early detection of their construction and/or modification. Often, such facilities are placed in remote areas and search for their presence or routine monitoring can be a problem. Multispectral change detection with a broad-area sensor could serve a broad-area search function. Detection of construction activity has been shown to be possible with LANDSAT data and future systems should have added capability. Detection and identification of effluent gases with HS/US sensors could also aid facility detection and characterization. There is the possibility of improving IFFN capabilities by introducing hyperspectral markers into the paints and/or fuels of friendly equipment. These would introduce characteristic spectral absorption lines into reflected or emitted spectra. Multispectral systems have long been used to support environmental assessments, resource assessments, natural disaster assessment infrastructure mapping, and so forth. This type of information will become increasingly important to Unified and Specified (U&S) commands for non-war planning and operations assistance.

Relationship to Commercial Developments

The Air Force can leverage commercial development of thermal infrared focal plane arrays, mostly in the 3 to 5 micron region, to reduce sensor cost. Most current commercial development of spectral sensors is in the 0.4 to 2.5 micron region. Commercial thermal infrared spectral sensors will be developed later. There are some important commercial applications such as mineral exploration, and pollution detection that will benefit from these sensors. Satellite and airborne EO sensors of today are primarily the result of governmental funding. Direct government sponsorship has been common, because of the required amounts of technological development and the specialized needs of military users and other government users. In those cases where governmental organizations do not have complete ownership of space assets, heavy subsidization has been the rule, as in the French SPOT system and Japanese MOS and JERS systems. In the

U.S., LANDSAT was commercialized for a period of several years, but was not able to stand alone without substantial subsidy. After the failed launch of LANDSAT 6, the U.S. government resumed its lead role for future LANDSAT. The SeaWiFS program represents a more recent venture into commercialization of multispectral imaging systems. Commercial satellite imaging appears to be taking two thrusts, both of which are seeking markets that would yield large-volume data sales. One thrust is toward high-resolution panchromatic data (e.g., 1 to 3 meters) for engineering and land-use applications, as well as imagery for the news media. The other thrust, more pertinent to the topic of this paper, is toward multispectral data for agricultural and other earth resource applications. Of particular interest are market segments, such as high-technology prescription farming and high-value cropping, which could substantially benefit from advanced remote-sensing technology. Projecting 10 to 20 years in the future, panchromatic and multispectral data of fine spatial resolution may be directly downlinked to major users, perhaps through a relay satellite. Hyperspectral data also may be available, but on a more restricted basis. Rather than transmission of all spectral channels, users will likely be able to select only those most important for the particular need being addressed. A key to exploitation of MS and HS image data will be the ability to spatially register them to geographic coordinate systems and allow referencing to other types of information in geo-referenced databases. It can be anticipated that commercial remote sensing data will satisfy nontime-critical AF MS information needs such as terrain analysis, infrastructure changes bathymetry, and so forth, which could be served from a data archive refreshed every few months or yearly.

The Air Force could leverage off commercial activities in any of several ways, including buying commercial data. This approach frees the government of system maintenance responsibilities and long-term investments in infrastructure. Possible disadvantages include less control over system characteristics and restricted ability for prioritization and control of information to adversaries during times of conflict. Amelioration possibilities include purchase guarantees, augmentation of sensor development costs for more timely development of new capabilities or addition of specific capabilities, and agreements about government intervention during times of conflict. Data purchased from commercial MS and/or HS imaging systems could likely fill some Air Force mission needs. For instance, spectral imaging should be adequate for generating terrain categorizations for intelligence preparation of the battlefield and similar functions. The Air Force might increase timeliness of data from a commercial system by subsidizing the cost for additional satellites, so as to increase revisit opportunities. The Air Force could investigate placement of its own sensors aboard commercial platforms and using the commercial data links for data retrieval. The Air Force could provide funding for performance enhancements of commercial sensors that go beyond existing commercial needs. Environmental monitoring is an important concern of the civilian and commercial communities. Technologies developed to monitor facilities and detect releases and improper disposal of pollutants and wastes could also serve or be adapted to related military missions.

Impact on Affordability

Although thermal infrared spectral sensors in themselves may be more expensive than current Air Force thermal imagers, they could substantially reduce mission costs by reducing the amount of operating time required to perform the mission. The dramatic drop in required flight time to accomplish a mission will also result in many fewer lost aircraft, a savings in money as well as Air Force lives. We also will have fewer false targets, so we will waste fewer

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weapons. Intelligent preparation of the battlefield and chemical detection could also have major impacts on the effectiveness of our forces and therefore on the cost to achieve mission objectives.

Recommended Development Plan

Continue the joint multispectral program to conduct multispectral imaging tower tests, followed by multispectral imaging flight tests. Continue development of a first principals understanding of the required band pairs for maximum clutter rejection, verifying theoretical hypotheses using the collected imaging multispectral data. Once enough understanding of the phenomena is achieved, begin sensor design. IR sensors in the 3 to 12 micron band with 0.1 micron bandwidth and tunable over a yet unknown subset of the available wavelengths will be required.

Initiate an active sensor/ultraspectral sensing task, with the goal of identifying partially obscured targets. In particular, strive for target recognition with high values of target obscuration, such as 95 percent.

Consider change detection systems deployment to take advantage of the large scale changes over time due to construction of facilities and so forth.

6.2.8.2 HF/VHF Radar and Seismic Tomography for Observation of Underground Structures and Environment

Technological Approach

There is an increasing need for underground observations of both the geological environment and manmade structures covering volumes of the order of 100 to 1000 meters in size with resolution from a meter to a few tens of meters. Such a capability would find both important military and civilian applications. For example, military operations often require knowledge of underground structures, such as tunnels, bunkers and underground manufacturing facilities. In the civil sphere, the emphasis is on three-dimensional maps of the geological setting, including soil and rock types, fissures and voids as well as manmade structures. Some specific applications are in civil engineering construction and clean up of leaking underground storage containers.

The concept is to use both electromagnetic and seismic waves transmitted from underground sources to underground sensors. One issue is the transmission of the electromagnetic wave. However, this concept uses two distinct types of sensors and therefore fits in the category of expanded dimensionality. Observations between a number of source and sensor sites surrounding a region to be surveyed would be used in a tomographic scheme to construct a three-dimensional map of the electromagnetic and seismic properties of the volume observed. These data would then be interpreted in terms of geological characteristics and manmade structures.

Some characteristics that are likely to be useful are signal amplitude and phase, time delay of both the first arrival and subsequent arrivals reflected or refracted by the underground structure (natural and manmade), change in signal strength with frequency and coherence of the received signal. For example, signal time delay along a path allows calculation of average propagation speed. Compressional seismic propagation speed varies from a few kilometers per second (varying with rock) to only 331 m/s in air. Thus, voids would show up as decreases in propagation velocity along a path. For small changes in propagation speed, signal phase would be the

appropriate observable. Electromagnetic waves, on the other hand, travel more slowly in rock than in air and thus voids would show up as increases in the average group propagation speed. The important point here is that seismic waves respond to mechanical (elastic) properties of materials while electromagnetic waves respond to the electrical properties of materials. Thus, by using both types of waves one can gather a much better data set from which to map out estimates of the underground structure of a site.

To implement this electromagnetic/seismic tomographic scheme, one needs to use wavelengths that are short enough to provide good spatial resolution, yet long enough to limit propagation loss to a level such that signal to noise ratios are in the 10 to 20 dB class. Sensor capabilities need to be considered. A first order estimate for ranges of 100 to 1000 meters indicates that electromagnetic waves in the meter to perhaps a few tens of meters and seismic waves from perhaps large fractions of a meter to ten meters are appropriate. Sources and sensors for both electromagnetic and seismic waves exist, and most have been used in underground sensing applications. Improvements in sources and sensors are likely, but are probably not necessary for testing the idea in a realistic situation. Emplacement by penetrating devices is possible, but not to the depths of deep bore holes.

Relationship to Air Force Missions

Air Force missions are increasingly likely to require knowledge of underground structures for targeting of command bunkers and vehicles emerging from underground structures as well as the structures themselves. As the Persian Gulf War demonstrated, precise placement of munitions is a great advantage in destroying enemy forces and material. The scheme above allows such precise location, that is, it allows one to move from a vague idea of the location of a possible underground structure (km) to precise location (meters) in both horizontal coordinates and depth. In general, one would be denied access to a site and would need to emplace sources and sensors by covert means, for example, penetrators deployed by aircraft. However, in some cases surveys of known sites can be made for future use, for example, in peacekeeping and treaty enforcement missions.

Relationship to Commercial Applications

Surveys of underground sites on the size scales described here have commercial applications in both civil and environmental engineering. In civil engineering, the construction of highways, buildings or other large structures requires a survey to insure the competence of the rock below the site. Otherwise, subsidence may occur from unknown voids. Environmental clean up is another important commercial application. The conventional method is to use test bore holes to characterize the site geologically. This method is both costly and invasive. For example, a bore hole may allow pollutants trapped above an impermeable layer to escape to layers below by passing through a test bore hole and its surrounding fractures of the layer. Once an accurate survey of the contaminated region is done, a plan can be devised to remove or mediate the pollutants in a cost effective manner. In particular, an underground survey allows modeling of pollutant flow, and thus one can make a targeted search rather than having to excavate a larger volume. Mineral exploration may be able to use similar techniques. Also, archeologists certainly would be interested in finding underground cavities.

6.2.8.3 HF/VHF/UHF SAR for Foliage and Ground Penetration

Description of Technology

HF/VHF/UHF SAR has the potential to detect and classify military targets concealed by foliage and objects/targets buried at shallow depths. It is also expected that metallic objects inside manmade structures such as buildings will be detected by this kind of radar. In summary, the HF/VHF/UHF SAR has the potential to penetrate line of sight obscuring materials while imaging the desired object of interest.

Current radar system concepts indicate a VHF/UHF SAR will use a very wideband waveform, and can be classified as an ultra-wideband (UWB) radar. The pulse bandwidth could easily be in the 400 to 600 MHz range with a center frequency of 300 to 500 MHz. Typical spatial resolution needed is 0.5 meter in both range and azimuth to provide adequate clutter suppression. [Three-dimensional aperture concepts to help resolve clutter in a volume cell (voxel) are also a possibility.] The radar will transmit and receive a complete set of polarizations, that is, it will be a polarimetric radar. This too is needed for clutter suppression. The radar will also need to provide for multiple images (looks) over a 90 degree interval. This angle diversity is needed to enhance the target signature. The radar system concept needs the fine resolution, multiple polarizations, and multiple looks to reliably detect the targets under foliage with a false alarm rate of less than one per 10 square kilometers.

The main technology issues for this radar are ultrawideband antenna and transmitter components, affordable high throughput signal processors providing 100's of gigaflops/sec, and robust target detection algorithms. The capability of this technology to provide reliable target classification is yet to be proven.

Development Status

This technology is under development (6.2 and 6.3a) and is showing good potential. An airborne test radar developed under primarily ARPA funding, with some support by the Air Force and Navy, has recently started flying and collecting data to determine the performance in detecting military targets. This testbed is the P-3 UWB SAR flying on a NAWC P-3 aircraft. The ARPA FOPEN (foliage penetration) program conducted many experiments with existing radars prior to developing the P-3 UWB SAR. This radar provides for 500 MHz of pulse bandwidth placed within the overall band of 200 to 900 MHz. It is also a polarimetric radar. It produces broadside looking strip map imagery. It does not provide multiple looks over a 90 degree interval as needed. Data collections can be done with multiple flight paths to acquire the equivalent of multiple look data. Also the P-3 UWB radar use an antenna and transmitter that were off the shelf, and they are not suitable for any operational aircraft except for a cargo size aircraft. The airborne radar from the A/Ds are recorded. The data are processed later to produce imagery.

The Air Force Wright Laboratories have also developed FOPEN technology in a program called Concealed Target Detection Technology Development (CTD program). Both LORAL and ERIM under this program investigated and modeled the phenomenology of foliage effects on radar signals propagating through the canopy, scattering from the canopy and from tree trunks. Signatures of targets were measured and modeled. This information was collected in a

simulation that was capable of producing radar imagery for targets under foliage. These data were then used to develop a target detection algorithm and to get a first assessment of expected performance. A simulation was used to produce imagery since there were no airborne radars with the appropriate capabilities. This was prior to the P-3 UWB SAR being built.

The Air Force Wright Laboratories has a follow-on CTD program under way called Radar Detection of Concealed Time Critical Targets (RADCON). This program is developing a real time image formation processor for the P-3 UWB SAR, and it is continuing to develop and refine target detection algorithms.

The implementation issues of the antenna and transmitter are not being addressed under any program. In addition, there are no plans for an operationally significant demonstration.

Current and Projected Performance

The VHF/UHF SAR will be capable of detecting targets concealed by foliage and targets buried at shallow depths. The FOPEN radar performance is characterized by parameters shown in Table 6-9.

The FOPEN performance shown in Table 6-9 will provide significant operational capability to detect military targets the size of trucks and larger under forest conditions typical of temperate zone conditions. The ability to classify targets with this technology is unclear and will be determined experimentally. Also it is not clear what detection performance can be achieved for targets under more difficult circumstances such as triple canopy jungle forests, as found in the equatorial regions. The level of attenuation produced by equatorial forests has not been measured. This prevents the prediction of target detection performance in equatorial regions.

The detection performance for buried targets is unclear at this time. Various experiments have been conducted. For example, the detection of recently buried 55 gallon oil drums has been demonstrated under typical midwestern soil at depths of 1 meter. Experiments in arid regions in the western United States have been less successful. This is due to the soils being more conductive than in the midwest or eastern areas of the United States. The detection of partially buried structures such as bunkers are projected but no experiments have been conducted.

Table 6-9. FOPEN Radar Performance

Performance Parameter	Current Performance	Projected Performance
Forest Type	Temperate zone (e.g., Europe)	Best performance in temperate zones but some capability in equatorial forests at higher grazing angles and for larger targets.
Detectable Targets	M-35 trucks and larger	artillery, and vehicles jeep size and larger
Probability of Detection	0.8 to 0.9	0.8 to 0.9
Probability of False Alarm	1.0 per square kilometer	1 per 10 to 100 square kilometers
Swath Width	0.8 km	5 to 10 km
Area Rate	4000 square nmi/day	20,000 to 40,000 square nmi/day
Grazing Angle Region	30 to 60 degrees	15 to 60 degrees for temperate zone forests, >45 degrees for equatorial forests

Relationship to Air Force Missions

The Air Force has the mission of detecting and classifying targets from airborne platforms to support the missions of interdiction and deep strike. Today, the Air Force cannot reliably detect and classify targets concealed by foliage. The use of concealment by foliage can be done by parking targets on roads or clearings in the forest, and by parking targets next to tree lines where the radar does not have clear line of sight. While this was not important in the Middle East, this capability is critical in most parts of the world including Korea, Europe, South America, and Southeast Asia.

Finding artillery and armor concealed by foliage today would be very difficult using existing Air Force assets such as the Air Force ASARS-2 radar flown on the U2-R aircraft. While this SAR was very useful in Desert Storm, it would not be nearly as useful in finding military targets where tree lines or forests could be used to prevent line of sight viewing of the target. The benefit of this technology being applied to Air Force missions of deep strike and interdiction is to enable prosecution of targets now successfully concealed by foliage, structures and earth emplacements. The Air Force will be much more effective in prosecuting armor concealed in forests or aircraft hidden in hardened structures.

Relationship to Commercial Developments

The processing capability required by a VHF/UHF radar is significantly larger than needed by current or near term SARs. Current SARs require approximately 10 Gflops/sec of peak computing capability. A VHF/UHF SAR will require 100's of Gflops/sec for acceptable performance. Affordable signal processing will be accessible by the Air Force by using COTS computing technology. The operational deployment of VHF/UHF SAR's will await affordable signal processing of 100's of Gflops/sec.

There is a potential commercial benefit of FOPEN radar for forest surveys by using the imagery to count trees and to determine trunk size. The scattering from tree trunks for HH polarization produces bright point responses in the imagery. These points can be counted to estimate tree densities. The amplitude of the point response indicates the size and moisture content of the tree trunk. The soil conditions also affect the amplitude of the point response and make it more difficult to determine tree trunk diameter. Surveys of the soil conditions at a very modest number of sites could eliminate this issue.

Another potential commercial application is the use of FOPEN SAR to do terrain elevation mapping under heavy canopies using two closely spaced passes. This has applications for resource exploration and management. Either interferometry or stereo are candidate approaches.

Recommended Development Plan

A comprehensive development plan is needed to (1) determine the conditions where the VHF/UHF SAR will adequately perform, and (2) to develop the subsystem components suitable for installation in Air Force aircraft such as the U2-R, cargo type aircraft or in future UAVs.

Phase 1. Duration 2 to 3 years

- Develop transmitter and antenna components suitable for high altitude operational reconnaissance platforms.

- Demonstrate utility of FOPEN imagery for automatic cueing of military targets using testbed FOPEN SAR.

- Demonstrate utility of FOPEN SAR in imaging land features under foliage.

Phase 2. Duration 3 to 4 years

- Demonstrate prototype system on operational system. Test under many foliage conditions and seasons.

6.2.9 Inertial Sensing, Geolocation and Positioning

Description

This sensing technology provides accurate, reliable, and affordable location information anywhere on the globe and in near-space surroundings. The information is obtained either internally via inertial accelerations integrated to velocity and position, or externally via radio, optical, or other external navigation aids. Most often, it is obtained from a combination of both methods, with inertial data providing accurate short-term information and external aids used to bound long-term error growth.

The technology is well established and has evolved gradually over time, experiencing only a few major revolutions. A condensed history of this evolution is shown in Figure 6-25, starting with the World War II time period when inertial measurement systems were first introduced to replace historical navigation methods based on stellar sightings, clocks and catalogs. The early inertial sensing technology used spinning mass gyroscopes on stabilized gimbaled platforms to provide a reference frame for proof-mass accelerometers. While this was compelling because it provided accurate and continuous position information independent of external references, the arrangement proved costly and unreliable. It was eventually replaced with optical gyroscopes (ring laser and/or fiber optic gyros) on stap-down platforms attached directly to a vehicle. In this new arrangement, embedded digital computers are used to transform the continuously changing reference frame of the platform back into a fixed frame for navigation. It is the combined development of airborne computers and optical gyroscopes that made this revolution possible. Reliability has improved dramatically, from MTBFs in hundreds of hours to many thousands of hours. Size, weight, power consumption, and cost have all declined. Based on current commitments, the strapdown optical technology is expected to dominate Air Force systems and commercial transports systems well into the 2020s.

External radio aids have evolved on a similar gradual time line. These systems began with the installation of radio transmitters at known locations so that ranging and/or direction finding to these sources allow receivers to calculate their location. Examples are the OMEGA system and LORAN. Their accuracy is relatively poor (measured in nautical miles) and their coverage is incomplete. This situation is experiencing a major revolution with the introduction of full constellations of GPS and GLONASS satellites. In effect, these systems place many radio transmitters in orbit, so that some are visible to receivers at all times, for global coverage. They also utilize frequencies and coding schemes that provide accuracy in the tens of meters for basic modes, meters for differential modes, and centimeters for so-called carrier-phase modes.

Sensing Function: Accurate, Reliable, Affordable Location Anywhere

1940   1950   1960   1970   1980   1990   2000   2010   2020

stars, clocks & catalogs

gimbaled, spinning mass

Inertial Sensing

strapdown, optical

int GPS/INS, mil, 1 deg/hr

??

MEMS

int GPS/INS, comm, 1000 deg/hr

Radio Aids

GPS / GLONASS

Omega, Loran
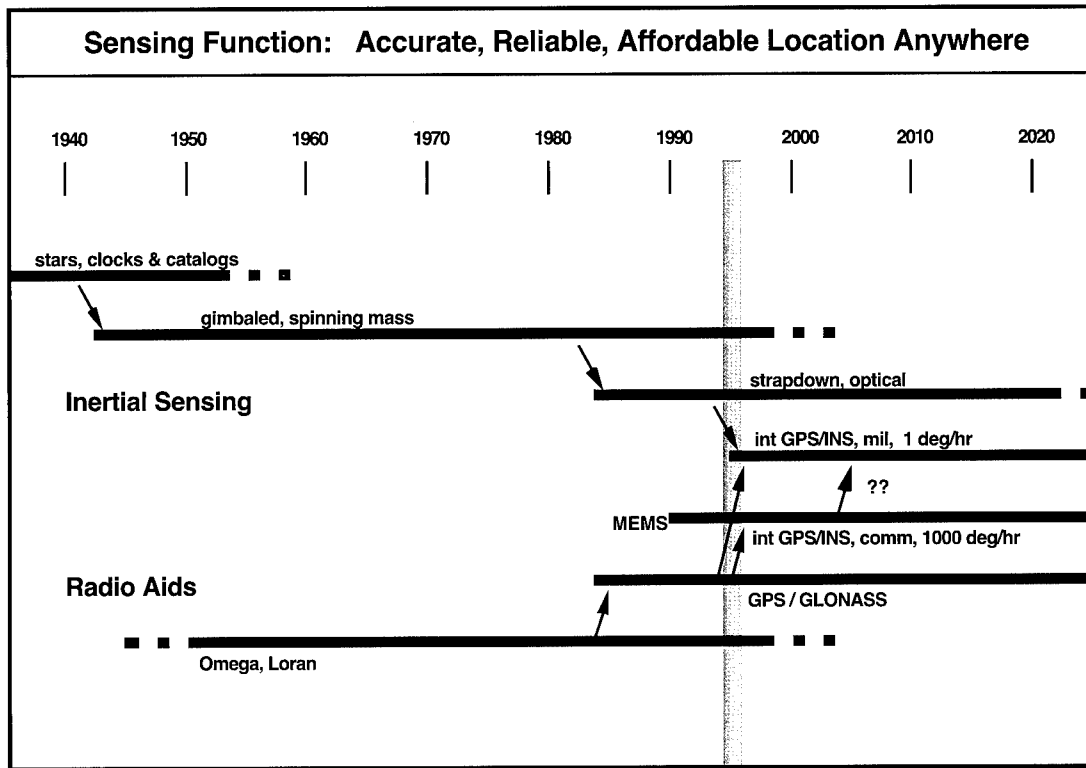
Figure 6-25. History of Geolocation and Positioning

One part of the ongoing GPS/GLONASS revolution is the growing trend to integrate these radio aids with inertial sensors in the same package. Such integration is occurring both in "loosely coupled" ways, where the radio aids are simply used in the navigation computer to bound long-term inertial errors, and in more "tightly coupled" ways, where the radio aids are used to continuously calibrate major inertial error sources (e.g., gyro biases) and the inertial data are used to help receiver tracking loops and antenna steering loops operate in adverse signal-to-noise environments. Loosely coupled integration is already common in new aircraft navigators, both military and commercial, while tight coupling will be widely used in weapons systems, where jamming is an important issue and where the inertial performance relief offered by tight integration promises cost reductions of today's strapdown optical systems.

Another aspect of the GPS/GLONASS revolution is the promise that a new very low cost inertial sensing technology may meet military needs. This is the MEMS technology described in Section 6.2.1. This technology relies on semiconductor processing methods from the microelectronics industry to make large numbers of very small mechanical structures with various useful properties. One useful structure, for example, is a vibrating tuning fork. In this structure, vibrations in one plane are transferred to an orthogonal plane through Coriolis-coupling whenever the structure is rotated. With electronics added to sustain the in-plane vibrations and to read-out the orthogonal response, the structure thus becomes a gyroscope. Some design concepts even

use micro-machined proof-mass accelerometers as the read-out scheme, so the structure also doubles as a linear accelerometer. Substantial R&D is currently on-going to design such devices for low cost commercial use in applications such as camcorder image stabilization, automotive suspension, braking and yaw control, and commercial vehicle navigation. These applications typically have gyro accuracy requirements of several thousand deg/hour. The closest military needs for tactical weapons, on the other hand, call for accuracy of a few deg/hour. Thus, a full three orders of magnitude currently separate commercial and military needs.

Relationship to Air Force Missions

Location information is a basic requirement for virtually all Air Force missions. It is required on all airborne platforms, both own-ship location and location relative to others. It is also required on all weapons except "dumb bombs" and on most vehicles or agents on the ground, down to individual airmen.

Relationship to Commercial Developments

As indicated above, the major trends today are the shift toward GPS as the primary radio aid for navigation, its integration with inertial sensors in the same package, and the development of very low cost MEMS devices as gyros and accelerometers. Commercial developments will drive the evolution of the GPS ground segment—the receivers, differential ground stations, and pseudolites for carrier phase concepts. This evolution will be driven by the pace of consumer electronics and communications technology. Similarly, low cost MEMS devices will be driven by commercial developments for consumer products such as automobiles and camcorders.

Development Plan

Basically, the Air Force should "go along for the ride" on the various commercial developments. It should exploit GPS evolution, undertaking its own developments only to cover un-addressed military needs (e.g., integrity, availability, jam resistance). It should also seek to drive MEMS technology into the tactical arena. The latter may prove very difficult, however, if "tactical" continues to mean 1 deg/hr gyro performance. These specifications are based largely on stand-alone requirements for inertial systems when GPS-aiding is disabled. Broader system level decisions that assure greater GPS availability could relax this requirement substantially and thereby encourage the use of MEMS devices in tactical systems.

6.2.10 Tagging Technology

This technology involves a wide variety of devices or materials that can be attached to targets of interest in order to clandestinely monitor their activity. During construction or periodic maintenance, vehicles will be under relatively light security and could be tagged. This would allow a continuous sampling of the target's activities and locations being visited that could include wartime security bunkers. Replacement of items like fuel caps with sensor caps would allow quick tagging. Agreement signing pens and award/gifts like watches would be another avenue to get tags on the desired target. Friendly troops can also be tagged to prevent accidental targeting. Some of these tags could be placed during inspection visits by attaching decals that would hide efficient flat patch antennas and retrodevices.

During manufacturing, military components of high value targets could be modified to provide a remote access to data and control systems, or to simply provide an ID number when transponded. There are many accessible approaches, such as through replacement tires, batteries, brake lights, light fixtures (provides battery charging), placards, bumpers, and printed circuit boards or chips, to name a few. The enemy's deployment and readiness state would be available by a polling of all sensors and noting the changes in location and other data like movement, engine on, computer up, and so forth.

Retroreflectors can be as simple as resonant optical spheres that look like ground-up ash. Items can be tagged with this powder and interrogated with pulsing laser sources. Optical grating arrays used as retros are able to modulate backscattered light at rates high enough to pass 20 nanosecond pulses. These speeds allow enormous amounts of data to be dumped in a quick strobe of the laser.

RF Retroreflectors

In the past, the Army communicated using the Heliograph, a device for signaling by means of a movable mirror that reflects beams of light, usually the sun. This passive concept could be useful again by operating in the microwave region of the spectrum to modulate radar backscatter energy. Instead of a mirror to reflect the sun, a set of resonant dipoles could be turned on and off with a simple diode switch, producing a modulated retro reflection. This modulation would identify the backscatter energy from the user's azimuth and range to be friendly.

The possible illuminator would be the Joint STARS platform or other coherent radars. The modulated retroreflector would appear as a unique Doppler target, say 100.15 miles per hour. Figure 6-26 depicts the concept. The power drain of the identification oscillator is exceedingly small with the life expectancy limited by the battery's shelf life. The optimum retro would be a cluster of tuned dipoles connected with diodes that all have the same source of identification data.
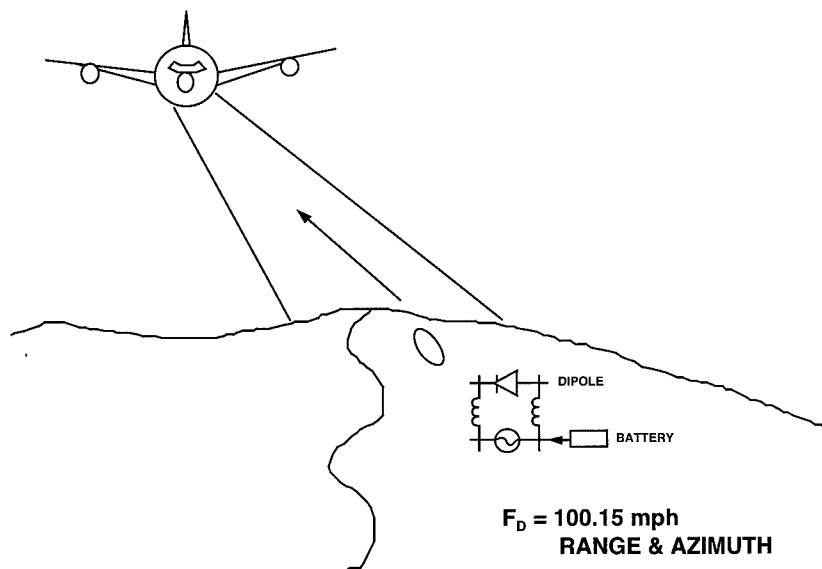

$F_D = 100.15$ mph
RANGE & AZIMUTH

Figure 6-26. Joint STARS Retroreflector Concept

Tire Tag Concept

A possible concept for tagging high value targets or associated vehicles using retroreflecting radar concepts could be accomplished by inserting snow studs into the rubber tread of a tire, constructed to resonate at the Joint STARS frequency to provide a chaff-like response with the Doppler offset generated by the tire's rotation. An ID number could be impressed on the return by switching the antenna diode.

Battery charging is possible using a piezo-electric crystal in the tip of the stud that is compressed on each contact with the road. As the tire rotates the response will be cross-polarized, producing a cyclic modulation that reveals vehicle speed.

Dual Purpose Tags

Most high-value tag targets have associated vehicles with power generators that require fuel tanks. Replacement of fuel tank caps with one of our Trojan horses would provide an easy access and concealment for a UHF transponder and a remote controlled squib that could rupture and ignite the fuel tank This would provide an excellent marker for other ordinances to take out associated targets. This type of device would be well suited for tagging Scud support trailers to tip off activity and destroy or mark weapons.

Parasite Tagging

The concept of parasiting on a target of interest by inserting a microdisc inside the cable connector, allows access to power from its battery bus and tapping data from the rest of the pins. Thin discs have been developed to provide a simple fix for RFI problems. These discs weigh one half gram each and easily slide onto the male pins of the typical cable connector. Current EMI filter wafers work by placing a discrete capacitor (or any other discrete electrical component) between each signal pin and ground in the host connector, significantly reducing radiated susceptibility and radiated emissions for new and retrofit applications.

The tag disc would perform exactly the opposite function by radiating the control data and adding an ID number. The sensor burst would then be transmitted on a selected frequency when interrogated by the collection platform. This microdisc does not appreciably change the size, shape, environmental seal, or electromagnetic compatibility of the host system. The wafers can be installed in under a minute by simply demating the host connector pair, inserting the disc, and remating the connectors.

Fuel Tagging

Laser fluorescing of engine exhaust particularly in aircraft has been demonstrated. To enhance this technique and to mark hostile aircraft, even stealth, very active fluorescing elements could be added to the general fuel supplies that will eventually get to the hostile combat targets. This will provide additional detection capability and help in identification of hostiles.

6.2.11 SIGINT and ESM

The use of signal intelligence (SIGINT), electronic (ELINT), communications (COMINT), and ESM for support to the warfighter, including both intelligence and operations, is an important sensor area. The intelligence support is well-known; and the support to operations must include

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direct support both as a cue to higher resolution sensors (SAR, for example), and as a direct targeting tool. The technologies are primarily those related to transitioning to all-digital signal processing.

6.2.11.1 Advanced SIGINT and ESM Technologies

Programmable All-Digital Receivers

The advancement of RF devices, along with the advancement of A/D converters and signal processing techniques, offers the opportunity to move the conversion to digital data for subsequent processing for signal detection and demodulation, analysis, and cataloging.

The fundamental desire is to convert an intercepted signal to digital data at the earliest possible stage, and process multiple digital channels with those algorithms that provide filtering, extraction from noise and co-channel signals, analysis, signal identification, and so forth. Thus, an architecture that achieves analog to digital conversion for frequencies from 100 MHz to 40 GHz is highly desirable. Moreover, as many as 100 or 1000 simultaneous channels might be necessary to handle all newly detected signals.

The key need is for high sample speed, high quality (spur-free, low aperture jitter, etc.) A/D converters. The state of the art at this time is 4 giga samples per second at 8 bits resolution for high quality conversion. Ultra high speed integrated circuit technology will bring the higher performance. (See Section 6.2.3.3 for more information on A/D converters.)

Signal processing techniques for some key analysis functions must be developed. While most functions are now accomplished by software at some nominal quality, the use of high speed digital processing offers the opportunity to significantly advance the ability to de-interleave signals, determine precise location, establish signal/system identity, and extract signal internals.

Micro-Signals Receivers

Some forms of equipment unintentionally radiate very low level signals of special importance to military operations. For example, computers radiate at their clock frequencies. While the content of the computing activity might not be radiating, the detection and location of the clock frequency radiation might provide the Special Operations forces with important information as to where in a building the computers are located, and even some information about type and quantity. Similar emanations can be expected from other equipments ranging from large machinery to digital watches.

Receiver technologies have improved significantly and it is likely that in the year 2025 we can expect to be able to develop a radiometric receiver on a chip with associated processing that would extract signals, including low probability of intercept signals, from electrically noisy backgrounds. The extremely small size would allow carrying the sensor extremely close to facilities and forces.

Wire and Cable Taps

From the U.S. Civil War through the Vietnam War, wiretap has been an important source of tactical intelligence. In the aftermath of "Watergate," the services dropped all tactical wiretap training and destroyed all equipments for fear someone might use it for some illegal purpose!

A robust sensor program should have the capability of providing access to enemy command communications that are currently secured in wire and fiber optics. The future is clearly moving to fiber optics to provide the wideband multiple user requirements of the future.

Net Analysis

A major limitation in tactical SIGINT is the ability to build a "cherry sheet" list of the enemy's net frequencies. This requires significant frequency activity to allow search operators to intercept and direction-find (DF) transmissions from the battle area of interest. The tactical field commander is primarily interested in data that come from the enemy that can cause harm. Radio silence is a standard practice for disciplined troops with only a quick communications check to assure readability by the net members.

A technique to assure high probability of intercept is an approach that uses a COTS radio frequency counter that has the ability to count the strongest signal's frequency in the 10 to 2800 MHz band. The counts are time tagged and store up to 400 events. For the field commander, this equipment could provide a first order analysis of externals and present an emitter map (electronic order of battle [EOB]).

The output data are also available for relay to remote collection (such as Rivet Joint) locations where a collection receiver would be automatically assigned to the detected frequency. This provides the operator a hands-free system. The intercepted traffic would confirm the user and provide intelligence on the target area of interest back to the commander. If a decision is made to jam the activity, the relayed counter readouts could be passed to resources such as Compass Call to allow a jammer to be on frequency in a very short time.

Spacecraft Sensor

The close-in technique discussed previously could be used in space to determine all intentional and unintentional transmissions emanating from an enemy satellite. The sensor spacecraft would be maneuvered in proximity to assure that any radiation will be easily detected over the background signals and noise. The locally detected signals would be characterized and a message sent to earth stations to allow large antennas and prepared receivers to be targeted against the satellite for collection. Especially low signal levels might call for collection in space. Other satellite emanations (magnetic, for example) could also be collected.

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7.0 Conclusions and Recommendations

As is evident from the contents of this Volume, the term "sensors" represents an exceedingly broad spectrum of technologies, concepts, and systems, all dedicated to provide the information and knowledge needed to successfully accomplish Air Force tasks. It has been a humbling undertaking to project this broad spectrum into the future and to speculate about its revolutions. Its results are, by definition, imprecise and incomplete. Hopefully, they will nevertheless prove useful to the Air Force in its planning for the future.

To manage this undertaking, the Sensors Panel of *New World Vistas* has used both a top-down and bottom-up look at the subject. The top-down view is captured by seven "Representative Operational Tasks" discussed in Section 4. These describe key Air Force tasks over the study's time horizon, and they identify information needs and notional sensing concepts to support those tasks. The bottom-up view is captured by the "Sensor Technology" descriptions in Section 6. These examine key sensing technologies as they exist today, project them into the future, and speculate about revolutionary advances that appear on the horizon. Some of the most promising of these possibilities are collected into several illustrative sensor concepts in Section 5. These demonstrate in more concrete fashion what the Air Force's sensing systems might look like in the future, and how they might be used to accomplish its tasks.

Beyond the many specific analyses, projections and recommendations contained in these individual sections, there are several overarching trends and opportunities that emerge from the study; these are summarized below. They lead to some general recommendations about how the Air Force can best participate in the trends, and what it should do to advance the opportunities.

7.1 Sensor Trends and Opportunities

7.1.1 Continuing Performance Improvement

The first, most evident trend in sensor technology is a continuing process of evolutionary performance improvement of traditional sensor systems and components. As described in Section 6, for example, Air Force radar systems are steadily advancing in resolution, bandwidth, ability to penetrate foliage and earth, MTI capability, levels of electronic integration, and in their various 'ilities. Likewise, electro-optical systems boast ever-denser focal planes with broader spectral response, on-chip tunability, and uncooled operation. Inertial systems, similarly, show steady improvement in drift performance, reductions in size and cost, increases in reliability, and ever-tighter integration with external aids. Supporting electronic components, such as A/D converters, I/O modules and embedded signal processors are also improving, becoming ever faster, smaller, less costly and more reliable. These trends can be expected to continue well into the time frame of this study.

7.1.2 Increasing Use of Multidimensional Phenomenology

A second trend in sensor technology is the growing use of multiple physical phenomena in the sensing process. Examples from Section 6 include multi, hyper, and ultraspectral imaging concepts that use information from several, many, or even continuously variable spectral bands. Other concepts combine information from optical and radio frequency bands, from vibration and polarimetry, from reflected spectra, from seismic and RF responses, and so on. Obviously,

the combinations are numerous. Their common characteristic is that they provide additional, often critically discriminating, information about objects of interest, allowing these objects to be detected and characterized with much improved error rates.

7.1.3 Increasing Interconnectivity

A third sensor technology trend is interconnectivity. This trend is already well under way and offers the means toward *New World Vistas* vision of "knowledge on demand," providing "global situation awareness" for Air Force planners and "complete knowledge of the battle field" for war fighters. In basic terms, interconnectivity exploits ever-improving communications and processing to move information gathered by many sensor systems to many users in near-real-time. This enables coordination and fusion and provides much greater knowledge extraction from spatial and temporal correlations of observations and events. It also enables global coverage, and permits needed resources to be focused onto specific regions of interest to gather fine-grained information as necessary.

Of course, interconnectivity by itself is not a panacea. There are difficult architectural questions concerning what sensors should be interconnected, what information should be communicated, in what form, when, to whom, under whose control, and under what levels of protection. These questions are discussed in Sections 2 and 3 and in other volumes of the *New World Vistas* report. They are large, largely unanswered, and will need major attention from Air Force system planners in the future.

7.1.4 Dramatic Algorithm Improvements

A fourth trend concerns computational algorithms for processing raw sensor data, distilling it down automatically into information and knowledge. This is an opportunity for the Air Force, rather than a trend, because it will not happen on its own. It must be caused to happen. Even in today's sensor systems, the data distillation step is a major weakness. There is not enough time to analyze the raw data manually and/or there is simply too much of it to move around in interconnected systems for display and use. Dramatic improvements are needed in algorithmic capability for basic sensor signal processing and for "intelligent" functions such as automatic target recognition, target classification, tracking, general pattern recognition, speech recognition, translation, and others. As described in Section 6, such improvements appear to be possible with appropriate R&D efforts exploiting the continuing growth of computational capacity and advances in computational architectures seen in the last decade. In the future, these algorithms will be critical to rapid exploitation and use of already vast and ever-increasing volumes of data gathered by our sensors.

7.1.5 New Enabling Technologies

Section 6 also identifies other technology opportunities that promise fundamental changes in the way sensors are designed and used. One of these is MEMS. This technology uses material processing methods from the microelectronics industry to make useful structures including pressure sensors, uncooled IR detectors, bio/chem detectors, accelerometers, gyroscopes, valves, and switches. The distinction is that these devices can be very small (down to lithography scales) and can be mass-manufactured with electronics already integrated, making unit costs potentially very low. Combined with communications and processing, these features enable sensing concepts

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comprised of many small distributed elements. Such concepts represent a major change of philosophy away from today's larger centralized systems. They also create entirely new sensing possibilities, some of which are described in Section 5.

A related emerging technology area is opto-electronics, which also uses microelectronics processing methods to build optical components integrated with electronics. These devices enable very small optical systems, pure delay elements, optically controlled microwave phased arrays and optical phased arrays, again supporting the sensor concepts in Section 5.

7.1.6 Commercial Trends for Affordability

Equally significant trends for Air Force sensors come from the commercial world, where certain technologies are applied in much greater volumes, driving affordability. Key ones of these are the continuing explosion of computational capacity (ever increasing MIPS per pound, watt and dollar), the growth of commercial interconnectivity (the information super highway), the exploding commercial use of GPS, the impending widespread applications of MEMS technology in consumer products, and the increasing availability of commercial systems for space launch, satcom, and satellite imagery.

7.1.7 New Concepts for Key Air Force Problems

Other opportunities identified in Sections 5 and 6 consist of several illustrative sensing concepts, including:

- A UAV "target reporter" for continuous long-duration surveillance of large battle areas

- An integrated array of distributed micro-sensors, including UGS packages, tags and other small flying or crawling mechanisms able to penetrate hostile facilities

- A surveillance concept for underground facilities (NBC, command and control, weapons storage, etc.)

- A concept for detecting concealed targets under all battlefield conditions

- A global weather surveillance and prediction concept

- A modular, integrated multifunction EO phased array

- A low cost space-based surveillance system using SAR radars and EO sensors on small satellites, launched on demand

These concepts combine various technology trends from above to solve key projected Air Force problems.

7.2 Recommendations

The trends and opportunities identified above call for concrete Air Force actions over the next few years and diligence extending well into the future. Trends should be exploited, and opportunities should be pushed forward toward real benefits.

Essentially, each item leads to a corresponding recommendation. First, for *evolutionary performance improvement* of traditional sensors, the Air Force must recognize and continue its

current role in bringing these improvements about through its R&D efforts and technology demonstrations. Key sensors such as radars, EO systems, inertial systems, and their supporting components will remain essential for the foreseeable future, and their continuous improvement remains a valid strategy.

Some specific improvements identified in Section 6 include affordable, broadband apertures for multifunction radar systems, integrated multifunction EO modules, and tactical navigation systems using micro-machined inertial devices.

The *multidimensional phenomenology* trend is less well established and needs to be nurtured energetically. Air Force programs should deliberately seek additional unexploited phenomena to clearly discriminate objects of interest in various difficult sensing situations.

As noted above, the third trend, *interconnectivity*, is already well under way. However, it poses difficult architectural issues and operational problems concerning information requirements and control. These call for major system design studies, trade-offs, and even organizational changes. Indeed, the Sensors Panel believes that the Air Force should designate a single central authority to define and control the information architecture and its sensor segments. The objective must be to halt the proliferation of stovepipe, non-interoperable systems and to begin migrating to the "system of systems" architecture described in Section 2.

A complicating factor is the current organization of Air Force laboratories along phenomenological lines (e.g., radar, EO/IR, ESM, ATR) instead of mission lines (e.g., surveillance, target attack). Full-time, mission application-oriented laboratory technical staffs created to supplement the Technology Planning Integrated Product Team (TPIPT) process provide a way to alleviate this problem.

Also already noted, the *algorithm improvement* trend is an opportunity that must be exploited. While the commercial world will contribute some of these improvements for problems such as automated inspection and assembly, military environments are typically much more variable and difficult. This calls for sustained Air Force involvement in the full spectrum of R&D, from basic theoretical foundations of algorithms, to advanced architectures and hardware for computation and data storage/retrieval, to early demonstrations and exploitation of extant capabilities in fielded systems.

In *emerging new technologies* and *commercial trends for affordability*, the Air Force must selectively act as prime mover of the technologies in some situations, and as intelligent user in other situations. The MEMS technology, for example, is a case where both stances are appropriate. Commercial uses of MEMS will provide many interesting components (pressure sensors, low-accuracy inertial sensors, valves, etc.) that can be applied in Air Force systems as appropriate. However, other components serving primarily military needs and/or military performance requirements (e.g., bio/chem sensors, tactical inertial sensors) will not likely be produced by commercial trends. The Air Force should therefore selectively invest in the MEMS technology, to influence processing methods and develop design concepts and device structures manufacturable on high-volume commercial lines, yet meeting military needs. In short, the Air Force should encourage true dual-use of MEMS.

Other commercial technologies are similar. The exploding consumer applications of GPS will provide ever smaller, cheaper receivers for potential military use. However, the Air Force

must insure that these devices can be adapted to meet military requirements, and particularly, that jam-resistant versions can be affordably built on commercial lines. Likewise, the continuing explosion of computational capacity will offer ever more affordable processing options that fundamentally change the way sensors and sensor systems are designed. In essence, cheap MIPS will be available to offset expensive mass in Air Force sensor designs. Yet, the Air Force must continue to insure that its special requirements on the processing capability (e.g., radiation hardness) continue to be affordable. Similarly, while the growing commercial infrastructure for interconnectivity and communications will provide affordable means of internetting sensors and users, Air Force investments must insure security, availability, and robustness for times of stress.

In summary, we offer the following specific recommendations:

1. Establish a central authority to define and control the information architecture, and its sensor segment, as a system of systems

2. Improve multifunction radio frequency apertures (see Section 6.2.3)

3. Improve multifunction electro-optical/infrared modules (see Section 6.2.2)

4. Develop a family of air-monitored, unattended ground sensors (see Section 5.2.2)

5. Develop a family of micro-sensors for use in airborne, spaceborne, and ground sensor systems (see Section 6.2.6)

6. Develop tags for air-monitoring the movement of materials and equipments (see Section 6.2.10)

7. Stress sensor affordability through emphasis on revolutionary and evolutionary signal processing concepts (see Section 6.2.4)

8. Exploit the advantages of the multidimensionality offered by multiple sensor regimes (see Section 6.2.8)

9. Develop ATR and ASC for sensor systems (see Section 6.2.5)

10. Finally, the Air Force should initiate programs to develop some of the *new concepts* identified in Section 5 or, at minimum, to develop and demonstrate their supporting technologies. Specific development programs should include:

    - A family of military-capable microsensors for acoustic, seismic, inertial, pressure, bio/chemical, and other phenomena.

    - A variety of doping materials and tagging devices to help locate and track weapons systems, munitions, vehicles and personnel.

    - A program in unattended ground sensors, using dopants, tags and internetted sensors from above, together with communications and fusion processing, to obtain detailed battlefield surveillance. The common need to activate and read-out these devices from airborne platforms justifies strong Air Force involvement in this technology.

These programs provide key capabilities for an overall sensing "system of systems" architecture leading to *New World Vistas* general vision of "knowledge on demand."

Appendix A

Sensors Panel Charter

In concert with the *New World Vistas* theme of "identifying fields of rapid technological change that are likely to revolutionize the 21st century," the Charter of the Sensors Panel is to identify new sensor concepts and technologies which, if pursued, will have strong impact in satisfying important military needs in the future in terms of greatly improved performance and/ or affordability. Opportunities to cooperate with commercial developments and dual-use implications are also important factors in identifying the key sensor concepts and technologies to be pursued.

Appendix B

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Appendix C

Panel Meeting Locations and Topics

7 March 1995   Washington DC

> Forecasting Methodology,
> ARPA Sensor Technologies,
> NRL Sensor Technologies

27 April 1995   Washington DC

> AFOSR Sensor Technology,
> Challenging Applications to Sensor Technology Mapping,
> Review of Candidate Sensor Technologies

3 May 1995   Maxwell AFB AL

> FPA,
> Hyperspectal Sensors

18-19 May 1995   Washington DC

> FPA, Hyperspectral Sensors,
> Optical Phased Arrays,
> Optical Target Recognition,
> MASINT Sensors, Counter-Proliferation

7-8 June 1995   Kirtland AFB NM

> FPA Technology,
> Hyperspectral Sensors,
> Active Sensors,
> Chem/Bio Sensors (LLNL)

22-23 June 1995   Washington DC

> Ultra-Wideband SAR,
> OTH Radar,
> Foliage Penetration Radar,
> Counter-Proliferation,
> Distributed Surveillance

Appendix D

List of Acronyms

Acronym	Definition
2-D	Two-Dimensional
3-D	Three-Dimensional
A/A	Air-to-Air
A/C	Aircraft
A/D	Analog-to-Digital
A/G	Air-to-Ground
ABCCC	Airborne Command Control, and Communications
ABL	Airborne Laser
ACIR	Airborne Coherent Imaging Radar
ACS	Aerosol-Particle Collection/Detection System
ACSC	Air Command and Staff College
ADC	Analog-to-Digital Conversion/Converters
ADPE	Automated Data Processing Equipment
AE	Acoustic Emission
AESA	Active Electronically Scanned Array
AF	Air Force
AGL	Above Ground Level
AFSOC	Air Force Special Operations Command
AI	Artificial Intelligence
a.k.a.	also known as
AM	Amplitude Modulation
AMOS	Air Force Maui Optical Station
AOIs	Areas of Interests
APD	Avalanch Photodiode
ARM	Anti-Radar/-Radiation Missile
ARPA	Advanced Research Projects Agency

ASC	Automatic Sensor Cueing
ASP	Adaptive Signal Processing/Processor
ATARS	Advanced Tactical Air Reconnaissance System
ATC	Automatic Target Cueing
ATO	Air Tasking Order
ATR	Automatic Target Recognition
ATS	Automatic Target Screener
AWACS	Airborne Warning and Control System
BDA	Battle Damage Assessment Bomb Damage Assessment
BIDS	Biological Integrated Detection System
BIT	Built-in Test
BITE	Built-in Test Equipment
BM	Ballistic Missile
BMDO	Ballistic Missile Defense Office
BPI	Boost Phase Intercept
BW	Biological Warfare/Weapon
C^2	Command and Control
C^3	Command, Control & Communications
C^3I	Command, Control, Communications & Intelligence
C^4I	Command, Control, Communications, Computers & Intelligence
CAS	Close Air Support
CBW	Chemical & Biological Warfare
CC&D	Camouflage, Concealment, and Deception
CCD	Charge-Coupled Device
CE	Capillary Electrophoresis
CELL	SurfaCe Emitting Laser Logic
CEP	Circular Error Probable
CFAR	Constant False Alarm Rate
CM	Cruise Missile
CMO	Central MASINT Office
CMOS	Complementary Metal-Oxide-Semiconductor (MOS)

CND	Can Not Duplicate
CNI	Communication, Navigation, & Identification
COG	Configureable Optical Gate
CONOPS	Concept of Operations
CONUS	Continental United States
COTS	Commercial-Off-the-Shelf
CP	Counter-Proliferation
CRDA	Cooperative Research and Development Agreement
CTD	Concealed Target Detection
CW	Continuous-Wave (Radar) Chemical Warfare
CWD	Concealed Weapon Detection
DAS	Detector Angular Subtense
dB	decibel
DC	Direct Current
DF	Direction-Find
DDL	Diode Laser Logic
DGPS	Differential Global Positioning System
DIAL	Differential Absorption LIDAR
DoD	Department of Defense
DPCA	Displaced Phase Center Antenna/Array
DRAM	Dynamic RAM (Random-Access Memory)
DSP	Digital Signal Processing/Processor
EDAC	Error Detection and Correction
ECM	Electronic Countermeasures
EDM	Engineering Development Model
EM	Electromagnetic
EMD	Engineering & Manufacturing Development
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
EO	Electro-Optical
EOB	Electronic Order of Battle

ERIM	Environmental Research Institute of Michigan
ESM	Electronic Support Measures
EW	Electronic Warfare Early Warning
FC	Fire Control
FET	Field Effect Transistor
FFT	Fast Fourier Transform
FIT	Fault Isolation Test
FLIR	Forward Looking IR (Infrared)
FM	Frequency Modulation
FOG-M	Fiber Optic Guided Missile
FOPEN	Foliage Penetrating (Radar)
FOV	Field of View
FPA	Focal Plane Array
f_T	unity-current-gain frequency
G	Gravity
GBR	Ground-Based Radar
GEODSS	Ground-based Electro-Optical Deep Space Surveillance
GIS	Geographic Information Systems
GMTI	Ground Moving Target Indicator
GPEN	Ground Penetration Radar
GPS	Global Positioning System
GSPS	Giga Samples per Second
GTD	Global Topographical Data
HAE	High Altitude Endurance
HBT	Heterostructure Bipolar Transistor
HF	High Frequency
HPT	Heterostructure Photo Transistor
HR-RTR	High Resolution Real-Time Radioscopy
HS	Hyperspectral
HUMINT	Human Intelligence
HYDICE	Hyperspectral Sensor

I&W	Indications & Warning
I/O	Input/Output
I/T	Integration/Testing
IC	Integrated Circuit
ID	Identification
IEEE	Institute of Electrical & Electronics Engineers
IFF	Identify Friend, or Foe
IFFN	Identify Friend, or Foe, or Neutral
IFSAR	Interferometric Synthetic Aperature Radar
IMA	Integrated Multifunction Aperture
IMU	Inertial Measurement Unit
INL	Integral Nonlinearity
INS	Inertial Navigation System
IPB	Intelligence Preparation of the Battlefield
IPL	In-Plane Laser
IR	Infrared
IRCM	Infrared Countermeasures
IRS	Indian Remote Sensing (satellite)
IRST	Infrared Search and Track
JAST	Joint Advanced Strike Technology (program)
JDL	Joint Directors of Laboratories
JERS	Japan Earth Resources Satellite
JFACC	Joint Force Air Component Commander
JFC	Joint Force Commander
JSTARS	Joint Surveillance & Target Attack Radar System (a.k.a. Joint STARS)
Joint STARS	Joint Surveillance & Target Attack Radar System (a.k.a. JSTARS)
LADAR	Laser Detection and Ranging
LAN	Local Area Network
LANDSAT	Land (survey remote sensing) Satellite
LANTIRN	Low Altitude Navigation & Targeting IR for Night
LCC	Life Cycle Cost

LE	Law Enforcement
LED	Light Emitting Diode
LIDAR	Light Detection and Ranging
LIF	Laser-Induced Fluorescence
LLNL	Lawrence Livermore National Laboratory
LO	Low Observable
LOC	Lines of Communication
LOP	Lines of Position
LPI	Low-Probability-of-Intercept
LSI	Large Scale Integration
LWIR	Long-wave IR (Infrared)
MALDI-TOFMS	Matrix-Assisted Laser Desorption/Ionization Time-of-Flight Mass Spectrometry
MASINT	Measurements and Signals Intelligence
MBE	Molecular-Beam Epitaxy
MCD-D	McDonald-Douglas Mechanical Systems
MEMS	Micro-Electro-Mechanical Systems
MILSTAR	Military Strategic & Tactical Relay
MIMIC	Microwave & Millimeter Wave Integrated Circuits (program)
MIPS	Mega Instructions per Second
MIT	Massachusetts Institute of Technology
MIT/LL	MIT/Lincoln Laboratory
MLD	Missile Launch Detection
MLW	Missile Launch Warning
MMIC	Monolithic Microwave Integrated Circuits
MMW	Millimeter Wave
MOOTW	Military Operations Other Than War
MOS	Metal-Oxide-Semiconductor
MOTIF	Maui Optical Tracking & Identification Facility
MPP	Multi-Pinned-Phase
MRC	Major Regional Conflict

MS	Multi-Spectral
MSPS	Mega Samples per Second
MTBF	Mean Time Between Failures
MTBCF	Mean Time Between Critical Failures
MTF	Modulation Transfer Function
MTI	Moving Target Indication/Indicator
MW	Millimeter Wave
MWIR	Medium-wave IR (Infrared)
MWR	Missile Warning Receiver
NAV	Navigation
NAWC	Naval Air Warfare Center
NBC	Nuclear, Biological, & Chemical (warfare)
NCA	National Command Authority
NCTR	Non-cooperative Target Recognition
NDI	Non-Destructive Interference (Acoustic) Non-Destructive Inspection
NIJ	National Institute of Justice
NIR	Near IR (Infrared)
NLECTC	National Law Enforcement & Corrections Technology Center
NLECTC/NE	National Law Enforcement & Corrections Technology Center/Northeast Region
NPR	Noise Power Ratio
NRL	Naval Research Laboratory
NSDI	National Spatial Data Infrastructure
NUC	Nonuniformity Correction
NVG	Night Vision Goggles
NWV	New World Vistas
O&M	Operations and Maintenance
OA	Obstacle Avoidance
OCR	Optical Character Recognition
ODB	Optical Data Bus
OOTW	Operations Other Than War

OPO	Optical Parametric Oscillator
Ops	Operations
ORTD	Optical RTD (Resonant Tunneling Device)
OTH	Over-the-Horizon
PA	Product Assurance
PAIIN	Portable Automated Inspection Instruments
PCR	Polymerase Chain Reaction
PCS	Personal Communications Services
P_d	Probability of Detection
P_{dis}	Power Dissipation
P_{fa}	Probability of False Alarm
PGM	Precision Guided Munitions
Pixel	Picture Resolution Element
PL	Phillips Laboratory
QBIC	Query-by-Information Element
QE	Quantum Efficiency
QWIPS	Quantum Well Infrared Photodectors
R&D	Research & Development
RADCON	Radar Detection of Concealed Time Critical Targets
RAM	Random-Access Memory
RASS	Radio-Acoustic Sounding System
RCS	Radar Cross Section
Recce	Reconnaissance
RF	Radio Frequency
RL	Rome Laboratory
ROI(s)	Region(s) of Interest
ROIC	Read Out IC (Integrated Circuit)
ROM	Rough Order of Magnitude
ROW	Rest of World
RPV	Remotely Piloted Vehicle
RRI	Riverside Research Institute

RSD	Relative Standard Deviation
RTD	Resonant Tunneling Device
RTOK	Retest OK
RV	Re-entry Vehicle Reconnaissance Vehicle
RWR	Radar Warning Receiver/Radar
S&T	Science & Technology
S/W	Software
SAR	Synthetic Aperture Radar
SAW	Surface Acoustic Wave
SBIR	Small Business Innovation Research
SEAD	Suppression of Enemy Air Defences
SEED	Self-Electro-optic Effect Device
SFA	Segmented Flow Analysis
SFDR	Spurious-Free Dynamic Range
SGMTI	Slow Ground MTI (Moving Target Indication)
SIGINT	Signal Intelligence
SMSR	Side-Mode Suppression Ratio
SNR	Signal to Noise Ratio
SO	Special Operations
SOAP	Spectroscopic Oil Analysis Program
SOF	Special Operations Forces
SOI	Space Object Identification
SO/MOOTW	Special Operations and Military Operations Other Than War
SPR	Statistical Pattern Recognition
SRAM	Static RAM (Random-Access Memory) Short-Range Attack Missile
STAP	Space-Time Adaptive Processing
STC	Stanford Telecommunications
STTR	Small Business Technology Transfer Program
SWIR	Short-wave IR (Infrared)
T/R	Transmit/Receive
TA	Terrain Avoidance

TAD	Tactical Air Defense
TBD	To Be Determined
TBM	Theater Ballistic Missile
TCS	Television Camera Set
TDI	Time Delay and Integration
TEC	Topographical Engineering Center
TEL	Transporter-Erector-Launcher
TERCOM	Terrain Aided Navigation
TF	Terrain Following
TI	Texas Instruments
TIMS	Thermal Infrared Mapping System
TIR	Thermal Infrared
TM	Terrain Mapping
TMD	Theater Missile Defense
TPIPT	Technology Planning Integrated Product Team
TSMD	Time/Stress Measurement Device
TV	Television
UAV	Unmanned Air Vehicle
UGF	Underground Facility
UGS	Unattended Ground Sensor(s)
UHF	Ultra High Frequency
UHR	Ultra High Resolution
UN	United Nations
US	Ultraspectral
UV	Ultraviolet
UWB	Ultra-Wideband
VAD	Vertical Azimuth Display
VCSEL	Vertical Cavity Surface Emitting Laser
VHF	Very High Frequency
VIS	Visible
V-LOGIC	Vertical Lasers with Optical Gain Control

VLSI	Very Large Scale Integration
VNIR	Very Near IR (Infrared)
VOC	Volatile Organic Chemical
WDM	Wavelength Division Multiplexed/Multiplexing
WL	Wright Laboratory
WMD	Weapons of Mass Destruction
wrt	with respect to

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